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PRIMARY (HYPOGENE) SULPHATE MINERALS IN ORE DEPOSITS.[1]

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INTRODUCTION.

In studying ore deposits the writer has several times been confronted with the problem of accounting for the formation of sulphate minerals that are apparently primary. These minerals occur at places where no evidence can be found of their formation by surface oxidation. Either they were formed directly by igneous emanations or, if they were formed by surface agencies, those agencies must have effected the deposition of other associated minerals that would ordinarily be regarded as of hypogene origin. An attempt will be made to analyze this problem by starting with the belief, based on deductions from field observations, that the sulphates in certain deposits have been formed directly by

[1] Published by permission of the Director, United State Geological Survey.

igneous emanations. To avoid complications the occurrence of the minerals in deposits that are not generally regarded as associated with igneous rock is discussed only incidentally. It is recognized that nearly all the sulphates that occur as apparently primary minerals in ore deposits associated with igneous rock have also been formed where they are not associated with igneous rocks. It is likewise recognized that in the formations of at least some of the primary sulphates in ore deposits that are associated with igneous rocks surface agencies may have played a part. The general conclusion reached is that some of the metals which at high temperature are combined with oxygen, as the temperature is reduced, give up oxygen, and both the metals and the oxygen combine with sulphur, producing sulphides of the metals and oxides of sulphur. At suitable temperatures the sulphites and sulphates are doubtless formed and the less soluble sulphates are deposited. Moreover, it is believed that certain conditions lead to the formation of free sulphuric acid which, on reaction with potassium-aluminum rocks, forms alunite.

SULPHATE MINERALS.

Brief summaries of the occurrence of the principal primary sulphate minerals in igneous rocks or of the sulphate minerals that are apparently primary in veins which are believed to be associated with igneous rocks are given below. No attempt is made to include in this summary occurrence of these minerals in other relations, or to give a complete list of localities.

Hauynite and Noselite.—Hauynite, $Na_2Ca(NaSO_4 \cdot Al)Al_2Si_3O_{12}$ and noselite, $Na_4(NaSO_4 \cdot Al)Al_2Si_3O_{12}$ are primary minerals in certain rather uncommon types of eruptive rocks such as those of the Cripple Creek volcano. It is noteworthy that these minerals are characteristic components of volcanic rocks, whereas the closely related chloride minerals are components of plutonic or deep-seated rocks.

Barite.—Barite, $BaSO_4$, is perhaps the most common primary sulphate vein mineral. It occurs usually if not invariably in

deposits formed at moderate and low temperature[2] or among the later minerals of deposits that contain minerals deposited at high temperature. Barite also occurs where it is not known to be related to igneous rocks.

It is difficult to determine even approximately the temperature at which any mineral deposit was formed, but Lindgren[3] has grouped the minerals in such deposits in three classes—those formed at low temperature (200° C. or less, perhaps much less), at moderate temperatures (175° to 300°C.), and at high temperatures (300° to 575° C.). Contact deposits may have been formed at much higher temperatures near that of magmas, which range from 800° to 1400° C.

Anhydrite.—Anhydrite, $CaSO_4$, has only recently been recognized as a primary vein mineral and its associations indicate deposition at moderate temperature. Anhydrite has the unusual property of decreasing in solubility with increase of temperature, being but slightly soluble at 200° C.[4]

It might be supposed that anhydrite would form most abundantly in deposits that replaced limestone, but the recorded occurrences do not justify this supposition. Probably the abundant carbon dioxide that must necessarily be present in solutions that are replacing limestone inhibits the precipitation of calcium sulphate.

Lindgren[5] first observed anhydrite as a vein-forming mineral in the Cactus mine, Utah, where it occurs in a vein in monzonite associated with tourmaline, hematite, pyrite, chalcopyrite, barite and siderite. Anhydrite, barite and siderite were among the latest minerals to form. Lindgren gave the following suggestion as to the origin of anhydrite:

[2] Emmons, W. H., "A Genetic Classification of Minerals," Econ. Geol., Vol. 3, p. 618, 1908.

[3] Lindgren, Waldemar, "Mineral Deposits," McGraw Hill Publishing Co., New York, 1913.

[4] Melcher, A. C., *Am. Chem. Soc. Jour.*, Vol. 32, pp. 50–66, 1910.

[5] Lindgren, Waldemar, "New Occurrence of Willemite and Anhydrite," *Science*, new ser., Vol. 28, p. 933, 1908.

It is suggested as a possibility that during the later part of mineralization the anhydrite was precipitated by a reaction between ascending solutions of sodium sulphate and descending solutions containing calcium carbonate.

The writer[6] accepted this interpretation, but with reservations and doubts that are among the motives which led to the preparation of this paper.

Anhydrite occurs in the Bully Hill district, Calif., in lodes in alaskite porphyry and is associated with pyrite, chalcopyrite, sphalerite and barite. Graton[7] apparently regards it as having been deposited directly from ascending solutions.

Boyle[8] also regards the gypsum and anhydrite of the Bully Hill district as of deep-seated origin, supposing that the calcium was derived from the limestone through which the solutions passed.

Anhydrite is reported from the Cobre district, Santiago, Cuba. The deposits are in andesite tuff cut by dikes of andesite. The associated minerals are pyrite, chalcopyrite and quartz.[9]

Geijer[10] describes anhydrite in deposits in Sweden associated with tremolite, galena, chalcopyrite and pyrite.

Hewett,[11] and Miller and Singewald[12] have described the remarkable deposits of the Minasragra vanadium mine of Peru. Hewett is quoted by Miller and Singewald as stating that the Veta Madre, which is a mixture of earthy material, disseminated sulphide of vanadium, and anhydrite, the last largely altered to gypsum for 120 feet below the surface, represents shale that has

[6] Butler, B. S., "Geology and Ore Deposits of the San Francisco and Adjacent Districts, Utah," U. S. Geol. Survey Prof. Paper 80, p. 124, 1913.

[7] Graton, L. C., "The Occurrence of Copper in Shasta County, Calif.," U. S. Geol. Survey Bull. 430, p. 100, 1910.

[8] Boyle, A. C., Jr., "Geology and Ore Deposits of the Bully Hill Mining District, Calif.," *Am. Inst. Min. Eng. Trans.*, Vol. 48, p. 111, 1915.

[9] Emerson, E. H., "Geologia de las minas," *Bol. de Minas,* Cuba, No. 4, pp. 47–52, 1918.

[10] Geyer, Per, Falutraktens berggrund ack malmfyndigheter, Geol. Survey of Sweden. Aorsbok, 1916, p. 156.

[11] *Am. Inst. Min. Eng. Trans.*, Vol. 40, pp. 274–299, 1909.

[12] Miller, B. L., and Singewald, J. T., "The Mineral Deposits of South America," pp. 487–491, McGraw-Hill Book Co., Inc., New York, 1919.

been more or less saturated by sulphide of vanadium and replaced by anhydrite.

Bastin[13] has described primary anhydrite and gypsum in the Braden copper deposits of Chile. The rocks and ores of the district record a complicated series of igneous events, including extrusions, intrusions and three distinct periods of mineralization. The first mineralization produced extensive tourmalinization with the deposition of relatively small amounts of pyrite and chalcopyrite. The minerals of the second period were mainly quartz, pyrite and chalcopyrite with small amounts of black tourmaline and a little biotite.

The metallic minerals of the third period include pyrite, chalcopyrite, bornite, galena, sphalerite, molybdenite, tennantite, enargite and hübnerite, and the gangue minerals siderite, rhodochrosite, calcite, anhydrite, gypsum and barite. The mineralization of the third period is thought by Bastin to have taken place at lower temperature than the earlier periods and was characterized by solution of tourmaline as contrasted with deposition of that mineral in the first two periods.

Anhydrite is also present in the copper deposits of Cuka-Dulkan at Bor, Serbia.[14] It is regarded by Lazarevic, however, as secondary.

Anhydrite occurs most abundantly where it is not associated with either igneous rocks or veins.

Gypsum.—Gypsum is a common mineral in ore deposits but has doubtless usually been formed by the alteration of anhydrite or by reaction between solutions of sulphuric acid (produced by the oxidation of sulphides) and calcium-bearing minerals. As already noted, Bastin considers gypsum in the Braden mine as primary.

Adolph Knopf has kindly furnished the following note on the occurrence of gypsum at the Utica mine, Calif.

The ore on the 2,100-foot level of the Utica mine, on the Mother Lode at Angels, Calif.,—a low-grade ore averaging $2 in gold—consists

[13] Bastin, E. S., private report based on detailed study.

[14] Lazarevic, M., "Die enargit-covellin-lagerstätten von Cuka-Dulkan bei Bor in Ost-Serbien," *Zeitschr. prakt. Geologie*, Vol. 20, p. 337, 1912.

of quartz and subordinate dolomite, gypsum, and, as shown under the microscope, albite. The only sulphide present is some extremely fine-grained galena disseminated in small patches. The vein, which is vertical, is inclosed in amphibolite schist, and the vein and country rock are so impervious and dry that the mine workings are dusty, although the mine above the 900-foot level makes large quantities of water. The gypsum is intimately intergrown with the quartz, and this fact together with its occurrence so far below the zone of oxidation and the obvious imperviousness of the vein to descending waters, suggest that the gypsum is a primary (hypogene) constituent of the ore. Under the microscope the gypsum is seen to be intergrown with quartz in patterns somewhat like micrographic intergrowths, and this feature possibly corroborates the evidence of its primary origin.

Celestite.—Celestite, like barite and anhydrite, occurs in deposits formed at intermediate to low temperature and also at many places where it is not associated with igneous rocks.

Alunite.—Alunite has the chemical formula $K_2O \cdot 3Al_2O_3 \cdot 4SO_3 \cdot 6H_2O$ in which Na may replace K in varying proportions. Alunite is perhaps the most abundant and widely distributed sulphate mineral that is associated with altered volcanic rocks. It occurs also as a secondary (supergene) mineral in the oxidized zone of ore deposits. Its genesis has been variously interpreted by different geologists, doubtless because it has been formed in various ways. The occurrences of the mineral have been summarized by Ransome[15] and later by Butler and Gale.[16]

Perhaps the best known deposit worked for alunite is that at Tolfa, Italy, where the alunite occurs in trachyte and is said to give place in depth to pyritic trachyte. Concerning the formation of the alunite De Launay says:[17]

Alunite is, in my opinion, a product of the decomposition of feldspar similar to kaolin, which is worked in the same region, and often from the same veins, and, like this kaolin, is bound to disappear in depth. The

[15] Ransome, F. L., "The Geology and Ore Deposits of Goldfield, Nev.," U S. Geol. Survey Prof. Paper 66, pp. 189–195, 1909.

[16] Butler, B. S., and Gale, H. S., "Alunite, a Newly Discovered Deposit near Marysvale, Utah," U. S. Geol. Survey Bull. 511, 1912.

[17] Translation by Butler, B. S., and Gale, H. S., *op. cit.*, p. 52, from De Launay, L., "La metallogenie de l'Italie," *Compt. Rend. Tenth Internat. Geol. Cong., Mexico,* pt. 1, 1907.

theory which was formerly held is somewhat different. It was thought that the sulphur vapors of solfataric kinds circulated in the fissures of trachyte and attacked directly in depth the feldspars of the latter, and a relation was supposed to exist between these different phenomena and the trachyte itself. I believe, on the contrary, that there are two entirely distinct phases in the phenomenon—first, a vein deposit clearly delimited, of pyritic trachyte corresponding, perhaps, to the veins of a trachyte particularly feldspathic and at the same time pyritic like the granulites of Berzowsk (Oural); second, penetration by superficial waters of the feldspathic rocks, producing, where pyrite fails, the ordinary forms of altered feldspars—that is to say, kaolin,—but where, on the other hand, pyrite furnished sulphuric acid, crystalline alunite.

Lindgren[18] and others have described the occurrence of alunite formed by the action of solutions that contained sulphuric acid, which were derived from oxidizing sulphides on potassium aluminum silicates.

In the United States there are numerous deposits of alunite which are believed to have been formed and others that are perhaps now forming by the action of hot sulphurous waters on potassium-alumnium rocks. Large bodies of volcanic rocks so altered are composed chiefly of quartz, alunite and pyrite. The calcium, magnesium, and sodium were largely removed from the original rock, but iron appears to have been converted to pyrite at the same time that alunite was formed. In discussing the origin of the gold deposits at Goldfield, Nev., Ransome[19] postulates:

> that the ore constituents were brought up in hot solutions charged with hydrogen sulphide, a little carbon dioxide, and probably also with some alkali sulphides; that the hydrogen sulphide was oxidized at and near the surface to sulphuric acid, which percolated down through the warm rocks to mingle with the uprising currents carrying sulphydric acid.

For the deposits near Marysvale, Utah, which occur as veins in effusive rocks and have been developed for the alunite, Butler and Gale say:[20]

[18] Lindgren, Waldemar, "The Copper Deposits of the Clifton-Morenci District, Ariz.," U. S. Geol. Survey Prof. Paper 43, pp. 119, 120, 1905.

[19] Ransome, F. L., *op. cit.*, p. 193.

[20] Butler, B. S., and Gale, H. S., *op. cit.*, p. 36.

The evidence in the Marysvale district, however, indicates that the materials constituting the veins were deposited by ascending solutions and that these solutions brought in the constituents of the alunite. At just what stage the sulphuric acid may have been formed can not now be positively stated, but it seems most natural to suppose that it was a part of the original solutions and that the potassium and aluminum were in part original in the solution and in part dissolved from the walls of the fissure at greater depth.

The veins in this district are nearly pure alunite but the altered wall rock is mainly alunite quartz and pyrite. Concerning alunitized rocks at Rico Mountains, Colo., Cross writes:[21]

The alteration of the porphyry of Calico Peak into a rock consisting largely of alunite, a hydrous sulphate of alumina and the alkalies, . . . can be explained only as the result of the attack of sulphurous agents, and from the circumstances of occurrence there can be no doubt that the action is to be attributed to solfataric emanations of the Rico eruptive center in the period of waning igneous activity.

Larsen has described several areas of alunitized rock in Colorado.[22] The altered rocks consist essentially of quartz, alunite and pyrite, one analysis giving: quartz, 69 per cent.; alunite, 29 per cent., and pyrite, 2 per cent. Concerning the genesis of these deposits Larsen writes:[23]

The evidence suggests hot ascending solutions as the cause of the alunitization. The field relations point strongly to deep-seated hot sulphuric acid solutions without the aid of the surface agents. However, in view of the fact that geologists do not generally admit the presence of such solutions, the evidence in the present case is not sufficient to justify the assumption of such a course for the alunitization in the San Cristobal quadrangle. The alternative source is the mingling of hot ascending solutions or gases carrying H_2S and of surface oxidizing waters.

Clapp[24] regards the deposit of Kynquot Sound, British Colum-

[21] Cross, Whitman, and Spencer, A. C., "Geology of the Rico Mountains, Colo.," U. S. Geol. Survey Twenty-first Ann. Rept., pt. 2, pp. 92–94, 1900.

[22] Larsen, S., "Alunite in the San Cristobal Quadrangle, Colo.," U. S. Geol. Survey Bull. 530, pp. 179–183.

[23] Larsen, E. S., *op. cit.*, p. 183.

[24] Clapp, C. H., "Alunite and Pyrophyllite in Triassic and Jurassic Volcanics at Kynquot Sound, British Columbia," ECON. GEOL., Vol. 10, pp. 70–88, 1915.

bia, as formed by "hot ascending solutions of volcanic origin and that at least these solutions causing alunitization carried free sulphuric acid."

A. L. Day and E. T. Allen have studied the hot springs of Mount Lassen, Calif., where alunite and pyrite are being deposited in the acid waters of the springs.[25]

Descriptions of occurrences of alunite could be multiplied, but the above seem sufficient to give the general modes of occurrence.

Hinsdalite.—Hinsdalite, $2PbO \cdot 3Al_2O_3 \cdot 2SO_3 \cdot P_2O_5 \cdot 6H_2O$, has been described by Larsen[26] and by Irving and Bancroft[27] from the Golden Fleece mine near Lake City, Colo. It is a primary mineral in a vein in volcanic rocks associated with pyrite, tetrahedrite, galena, pyrargyrite, quartz, rhodochrosite and barite. Barite is abundant also in neighboring deposits. The deposits are regarded by Irving and Bancroft as having been formed at shallow to moderate depth.

Creedite.—Larsen[28] describes creedite, $CaSO_4 \cdot 2CaF_2 \cdot 2Al(F, OH)_3 \cdot 2H_2O$, as occurring with barite and fluorite in a vein in Tertiary lavas near Wagon Wheel Gap, Colo. Larsen does not state whether he regards it as a primary or secondary mineral in the vein.

Thaumasite.—The unusual mineral thaumasite, $3CaO \cdot SiO_2 \cdot SO_3 \cdot CO_2 \cdot 15\ H_2O$, occurs in veins which cut contact altered limestone in the Old Hickory mine, Beaver County, Utah. It is regarded by Butler[29] as forming under conditions similar to those favorable to the formation of zeolites. The best known localities of this mineral in the United States are at West Paterson and

[25] Allen, E. T., personal communication.

[26] Larsen, E. S., and Schaller, W. T., "Hinsdalite, a New Mineral," Am. *Jour. Sci.*, 4th ser., Vol. 32, pp. 251–255, 1911.

[27] Irving, J. D., and Bancroft, Howland, "Geology and Ore Deposits near Lake City, Colo.," U. S. Geol. Survey Bull. 478, pp. 54–55, 1911.

[28] Larsen, E. S., and Wells, R. C., "Some Minerals from the Fluorite-barite Vein near Wagon Wheel Gap, Colo.," *Proc. Nat. Acad. Sci.*, Vol. 2, pp. 362–364, 1916.

[29] Butler, B. S., "Geology and Ore Deposits of the San Francisco and Adjacent Districts, Utah," U. S. Geol. Survey Prof. Paper 80, p. 104, 1913.

other localities in New Jersey, where it occurs in trap associated with zeolites.

Wilkeite.—Wilkeite,[30] $3Ca_3(P_2O_4)\cdot 3Ca_2SiO_4\cdot 3CaSO_4\cdot CaCO_3\cdot CaO$, occurs in contact altered limestone associated with wollastonite and garnet near Riverside, Calif.

Scapolite.—Scapolites occur as products of contact metamorphism and as alteration products of igneous rocks. Some of the scapolites contain the sulphate radicle.[31]

Svonbergite.—Svonbergite is apparently a rather rare primary mineral in ore deposits.[32]

CHARACTER OF ORE SOLUTIONS AS INDICATED BY VOLCANIC EMANATIONS.

The data concerning the composition of volcanic emanations have been summarized by many writers. A rather complete outline and bibliography has been prepared by Clarke,[33] who briefly summarized the results as follows:

> That the volcanic gases appear in a certain regular order has been shown by the various researches upon their composition, and especially by the labors of Deville and Leblanc. What, now, in the light of all the evidence, is that order, and what do the chemical changes mean?
>
> First. The gases issue from an active crater at so high a temperature that they are practically dry. They contain superheated steam, hydrogen, carbon monoxide, methane, the vapor of metallic chlorides, and other substances of minor importance. Oxygen may be present in them, with some nitrogen, argon, sulphur vapor, and gaseous compounds of fluorine.

[30] Eakle, A. S., and Rogers, A. F., "Wilkeite, a New Mineral of the Apatite Group, and Okenite, its Alteration Product from Southern California," *Am. Jour. Sci.*, 4th ser., Vol. 37, p. 262, 1914.

[31] Borgström, L. H., "Die skapolithlagerstätte von Laurinkari," *Com. géol. Finland*, Bull. 41, p. 23, 1913.

Brauns, R., "Skapolithführende Auswürflinge aus dem Laacher Seigebiet," *Neuss Jahrb.*, Beilage Band 39, p. 119, 1914.

[32] Lacroix, A., "Pyritiferous Deposits at the Contact of Granite at Chezeuil, Saone-et-Loire and its Metamorphic Rocks," *Bull. Soc. Franc. Min.*, 41, 14–21, 1918.

[33] Clarke, F. W., "The Data of Geochemistry," U. S. Geol. Survey Bull. 616, pp. 260–290, 1916.

Second. The hydrogen burns to form more water vapor, and the carbon gases oxidize to carbon dioxide. From the sulphur, sulphur dioxide is produced. The steam reacts upon a part of the metallic chlorides, generates hydrochloric acid, and so acid fumaroles make their appearance.

Third. The acid gases of the second phase force their way through crevices in the lava and the adjacent rocks, and their acid contents are consumed in effecting various pneumatolytic reactions. The rocks are corroded, and where sulphides occur hydrogen sulphide is set free. If carbonate rocks are encountered, carbon dioxide is also liberated.

Fourth. Only steam with carbon dioxide remains, and even the latter compound soon disappears.

This seems to be the general course of events, although it is modified in details by local peculiarities. All of the substances enumerated in the lists of gases and sublimates given in the earlier portions of this chapter may take part in the reactions, but they do not seriously affect the larger processes which have just been described. The order is essentially that laid down by Deville and Leblanc, except that the early evolution of hydrogen and carbonic oxide is taken into account. The current of events may be disturbed, so to speak, by ripples and eddies—that is, by subsidiary and reversed reactions—but its main course seems to be clearly indicated.[34]

Harker states:[35]

Different types of solfataric action might be distinguished, and these are in some degree characteristic of different kinds of lavas. But it is also to be remarked that different volatile constituents may figure prominently at a given volcanic center at different stages in decline of activity. This is in part a matter of direct observation; for it has frequently been remarked that only the hottest fumaroles emit hydrochloric and hydrofluoric acids, while sulphurous and hydrosulphuric acids are connected with lower temperatures of emission, and water and carbonic acid with the lowest temperatures. Some indications of a like sequence have already been noted in pneumatolysis under plutonic conditions.

[34] For a summary of our knowledge concerning the magmatic gases previous to the work of Brun and Chamberlin, see Lincoln, F. C., ECON. GEOL., Vol. 2, p. 258, 1907. Lincoln gives a good table of analyses and proposes a classification of the volcanic exhalations. For a theoretical discussion relative to "gas mineralizers" in magmas see Niggli, P., *Zeitschr. anorg. Chemie,* Vol. 75, p. 161, 1912, and Vol. 77, p. 321, 1912. Also *Centralbl. Mineralogie,* 1912, p. 321; and *Geol. Rundschau,* Vol. 3, p. 472, 1912.

[35] Harker, Alfred, "The Natural History of Igneous Rocks," p. 307, Methuen & Co., London, 1909.

The volcanic emanations contain carbon, hydrogen, sulphur, oxygen, nitrogen and minor constituents such as chlorine, fluorine and metals in varying proportions and combinations depending probably both on the original character and the temperature of the gases.

Day and Shepherd[36] collected gases from Kilauea with great care to avoid contamination with air, and state that the absence of argon "affords a most desirable confirmation of our belief that the volcano gases were successfully collected before they had come in contact with atmospheric air at all and were therefore entirely uncontaminated either by reaction or admixture with it." These gases were analyzed with the following results:

GASES FROM HALEMAUMAU (KILAUEA), MAY, 1912.
(Percentages by volume.)

	Tube 1.	Tube 2.	Tube 8.	Tube 10.	Tube 17.
CO_2	23.8	58.0	62.3	59.2	73.9
CO	5.6	3.9	3.5	4.6	4.0
H_2	7.2	6.7	7.5	7.0	10.2
N_2	63.3	29.8	13.8	29.2	11.8
SO_2	None	1.5	12.8	None	None
Rare gases	None	None	None	None	None
Hydrocarbons	None	None	None	None	None

These gases contained abundant water and before cooling more sulphur dioxide than is shown in the analysis. The authors say:

> The SO_2, for example, has gone over in part or altogether to SO_3 and gone into solution, and only two of the five tubes analyzed now show SO_2 as such. Moreover the resulting acid solutions may have reacted to a limited extent on the glass tube, and accordingly be responsible for all or a part of the alkalies, lime, and alumina shown in the analyses of water.

The writer understands that the authors do not suppose that any sulphuric acid was formed from original constituents on the cooling of the gases.

The analyses of the materials contained in the water are given in the following table:

[36] Day, A. L., and Shepherd, E. S., "Water and Volcanic Activity," *Geol. Soc. America Bull.*, Vol. 24, p. 588, 1913.

ANALYSES OF MATERIAL CONTAINED IN THE WATER COLLECTED IN THE TUBES.

	Tube 1, Grams	Tube 2, Grams
Na_2O	0.0214*	0.031*
K_2O	0.0102*	0.011*
CaO	0.0120*	0.14*
Fe_2O_3, Al_2O_3	0.080*	0.010*
Cl	0.220	0.206
F	0.565	0.492
NH_3	0.0018	None
TiO_2	0.005(?)	None
Total S as SO_3	0.480	0.508

* The major portion of these may have come from the glass or from Pele's hair.

The analyses recorded in the literature indicate that sulphur is present in different volcanic emanations as H_2S, SO_2, SO_3 and as sulphur vapor, and many of the analyses show free oxygen.

CONDITIONS OF FORMATION OF SULPHUR TRIOXIDE.

It is obvious that the first step in the deposition of the sulphate minerals is the formation of the sulphate radicle and the conditions under which this forms are therefore of interest. The commercial importance of sulphuric acid has led to careful investigation of the modes of formation of sulphur trioxide. Much information on this subject has been brought together by Lunge.[37]

Sulphuric acid can be formed in many ways, but one way in which it may be formed in igneous emanations is that known as the contact process. This process consists essentially in bringing about the combination of sulphur dioxide and oxygen by the aid of a catalyzer. The accompanying diagram, taken from Knietsch,[38] shows the reaction under different conditions at atmospheric pressure. Lunge[39] says:

> The most important result of Knietsch's experiments was that a line of stable equilibria exists which divides the range of temperature into

[37] Lunge, George, "The Manufacture of Sulphuric Acid and Alkali," 3 vols., New York, D. Van Nostrand Co., 1913.

[38] Lunge, George, *op. cit.*, p. 1307.

[39] *Idem*, p. 1311.

two parts [with the catalyzers used]. The range below 200° and above 900° or 1,000° may be called devoid of reaction in a technical sense; between 200° and 450° the reaction of formation prevails; above 450° the dissociation of SO_3 comes into play very rapidly.

For the purpose of this paper we may start at a temperature of 1000° at which SO_3 will be dissociated into SO_2 and O, and note the change that will take place on cooling.

It is apparent that the range of temperature in which sulphur trioxide forms at all rapidly and is stable under atmospheric pressure and in a system containing only sulphur and oxygen is not large.

In the manufacture of sulphuric acid the catalyzer commonly employed is platinum, but ferric oxide and many other substances act as catalyzers, so that many catalyzers may be present in mineral veins.

Another method of producing sulphuric acid, which is employed at the plant of the New Cornelia Copper Co., at Ajo, Ariz., should be mentioned here. In the treatment of copper ores the copper is leached by sulphuric acid and electrolytically precipitated. For successful precipitation it is necessary to keep the ferric iron of the solutions low. When the solutions become polluted with ferric sulphate that substance is reduced to ferrous sulphate by spraying the solution through a chamber containing sulphur dioxide.[40] The gas is cooled from 600° to 150° F. in passing through the chamber. The ferric iron in the solution is practically all reduced, according to the following reactions:[41]

$$Fe_2(SO_4)_3 + SO_2 + 2H_2O = 2FeSO_4 + 2H_2SO_4.$$

FORMATION OF SULPHURIC ACID IN NATURE.

The possible conditions under which sulphuric acid is formed in nature have been considered in detail by Ransome.[42] In dis-

[40] Tobelman, H. A., and Potter, J. A., "First Year of Leaching by the New Cornelia Copper Co.," Am. Inst. Min. Eng. Bull. 146, p. 475, 1919.

[41] *Idem*, p. 478.

[42] Ransome, F. L., "The Geology and Ore Deposits of Goldfield, Nev.," U. S. Geol. Survey Prof. Paper 66, pp. 189–195, 1909.

ISOCHRONOUS REACTION $2SO_2 + 3O_2 \gtrless 2SO_3 + 2O_2 + 22600$ CAL.

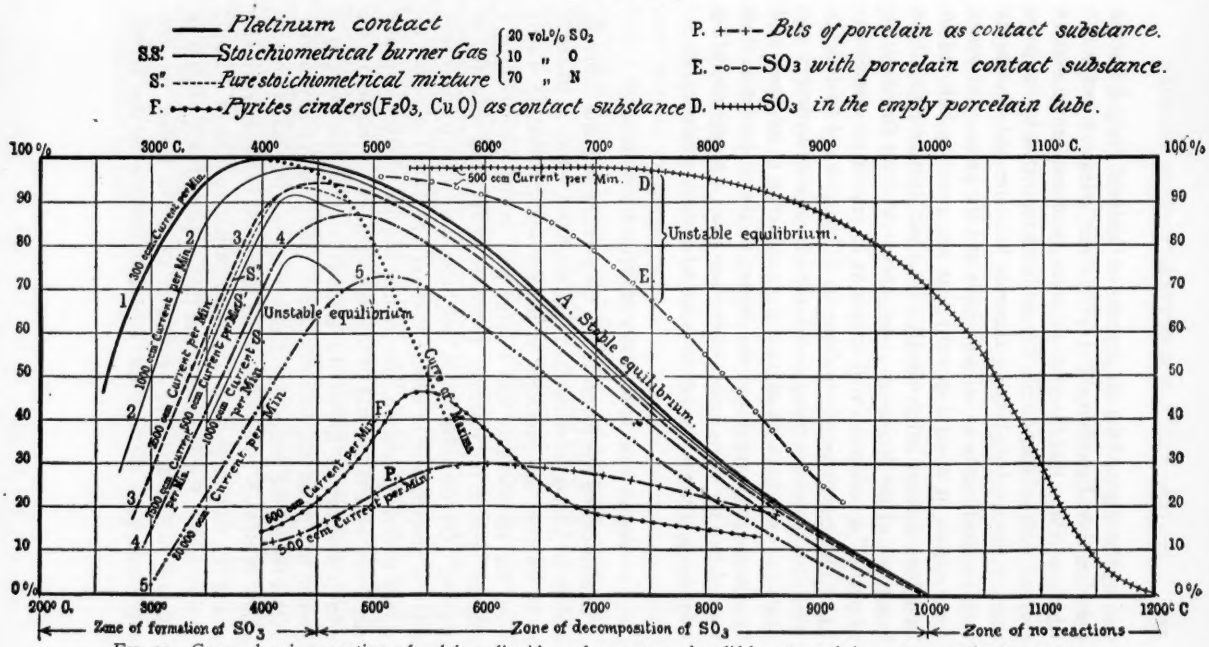

FIG. 39. Curve showing reaction of sulphur dioxide and oxygen under different conditions at atmospheric pressure.

cussing the origin of the ore deposits of Goldfield, Nev., Ransome considers three hypotheses: (1) "The direct volcanic hypothesis," which postulates that the solutions come from deep-seated sources charged with sulphuric acid, a hypothesis supported by the presence of the sulphate-bearing minerals hauynite and noselite as original constituents of volcanic rocks and the presence of barite and celestite in mineral deposits that are generally believed to have been formed independently of surface agencies; (2) "the hypothesis of the derivation of sulphuric acid from the oxidation of pyrite," a process so well known as to require no discussion; (3) "The hypothesis of simultaneous solfatarism and oxidation," which postulates the rising of solutions containing hydrogen sulphide to or nearly to the surface, their oxidation to sulphuric acid by atmospheric oxygen and the descent of the acid solution thus formed into the veins again, where they react with the ascending solutions and cause the precipitation of metals, sulphides, etc.

FORMATION OF PRIMARY SULPHATE MINERALS.

In considering the formation of the primary sulphate minerals, it must of course be recognized that sulphates, either as minerals or in solution, are prevalent at the surface and that, if waters from the surface have had a large part in the formation of a mineral deposit, the insoluble sulphates would most naturally be formed. On the other hand, sulphates are often found where there is good reason to believe that surface waters were not involved in their formation, and we may inquire whether sulphates can form without the aid of surface agencies. First let us see what consequences follow the assumption that free oxygen is present in a given magnetic emanation, even though many investigators regard the presence of free oxygen in a magma as improbable. With such an emanation the formation of sulphur trioxide would not only be possible but under certain conditions it would be inevitable. For instance, a gas that contained only sulphur or sulphur dioxide and free oxygen, at 1,000° or higher, on cooling would pass through the interval favorable to the forma-

tion of sulphur trioxide and that compound would form. At the higher temperatures, where sulphur trioxide is unstable, it would be in low concentration, and the formation and precipitation of abundant sulphates would not be expected, but where temperatures favorable to formation and stability were reached a high concentration might result, and there would be a proportionate tendency to the formation of sulphates. It is natural to suppose that barium present in the form of the more soluble compounds would be the first substance to be precipitated as sulphate on account of the very slight solubility of barite in ore solutions as indicated by its common occurrence. The same reasoning applies to some extent to the formation of anhydrite ($CaSO_4$) at high temperature and probably also to the formation of celestite. Barite is by far the most insoluble of the sulphates in pure water, and apparently also in mineralizing solutions, and, if it were not for this mineral, there would be little trace of sulphates as primary minerals except where near-surface conditions are reached. Such a development of sulphate would seem to be a more natural method for the formation of anhydrite, for example, than that suggested for the deposits of the Cactus mine, Utah, which did not account for the formation of the sulphate radicle. If the sulphate radicle actually forms in the cooling solution, it is easy to postulate a moderate supply of calcium from the alteration of the monzonite walls of the fissure from which it is known that much calcium has been removed. It is possible that under favorable conditions the sulphate radicle may form to an extent that would result in a solution containing sulphuric acid, which in rocks high in alkali and aluminum would at favorable temperatures give the conditions for the formation of alunite. As Ransome has pointed out, it is notable that solutions which form alunite apparently are not good carriers of metal. The Goldfield deposits are a distinct exception in their association with metallic sulphides, although cinnibar is associated with alunite in deposits east of Beatty, Nev., which have been described by Knopf.[43] The cinnabar occurs in

[43] Knopf, Adolph, "Some Cinnabar in Western Nevada," U. S. Geol. Survey Bull. 620, p. 64, 1916.

silicified and alunitized rhyolite. In the great alunitized areas there does not appear to have been extensive removal of iron, much of which, whether originally present as oxide or in silicates, seems to have been altered to pyrite and remained. In some of the deposits of the Marysvale, Utah region, hemalite is associated with alunite, but the relation of the minerals has not yet been carefully studied. Moreover the alunite in the vein is remarkably free from other minerals. When sulphus trioxide had developed in the cooling solution to the extent of yielding sulphuric acid the solution probably ceased to be a carrier of most of the metals,[44] and the formation of sulphur trioxide may possibly be a factor in the precipitation of the metals.

The behavior of smelter gases gives some indication of the temperature at which certain sulphates will form abundantly under given conditions. Fulton[45] says:

> The smoke stream also carries water vapor, the origin of which is the moisture in the ore charges fed to the furnaces. As long as the smoke stream has a temperature above 440° C., no combination of sulphur trioxide with water vapor to form sulphuric acid is possible, but as the temperature falls in the flues as the stack is approached, sulphuric acid vapor forms by the combination of water vapor and sulphur trioxide vapor, until at about 350° C. one half of the sulphur trioxide present in the smoke stream is in the form of sulphuric acid vapor. At ordinary atmospheric pressure (760 mm.) sulphuric acid, or rather a mixture of 98.54 per cent. of sulphuric acid and 1.46 per cent. of water, has a boiling point of 338° C. From this it follows that above 338° C. all sulphuric acid present must be in a vapor form or dissociated, but that below this temperature it may be present in the smoke stream in the liquid form as a fine mist or small liquid particles. . . . When the ore charge smelted or roasted contains a considerable percentage of volatile metals, such as lead, zinc and cadmium, these partly pass to the fume and, under oxidizing conditions, form oxides. The fine fume particles combine readily with the sulphuric acid formed, giving rise to sulphates and the consequent neutralization of the acid. The neutralization or the formation of sulphates probably does not readily take place until temperatures below 200° C. are reached, meaning practically that before sulphates are formed the sulphuric acid must be below its condensation point.

[44] Ransome, F. L., *op. cit.*, p. 195, suggests sulphuric acid as a precipitant.

[45] Fulton, C. H., "Metallurgical Smoke," U. S. Bur. Mines Bull. 84, pp. 25–26, 1915.

There seems little doubt that some sulphates will form at temperatures above 200°.

Certain theoretical considerations and facts of observation support to some degree the method of formation of sulphates here suggested. Sulphates would not be expected in deep-seated rocks, and apparently they are absent. They might form in low temperature magmas, but their abundant formation in such magmas would not be expected, and this seems to agree with observations. On the cooling of certain mixtures of gases, the formation of sulphur trioxide would be expected, and under certain conditions the formation of sulphates, and this seems to accord with the facts of observation.

The fact must not be overlooked, however, that the sulphates under discussion are associated with sulphides and were apparently deposited at the same time. The method would appear to make it necessary to suppose that sulphides were deposited in the presence of free oxygen.

We may next assume that free oxygen does not occur in the assumed magmatic emanation, and see if there is an available supply of combined oxygen for oxidation of sulphur to form sulphuric compounds. There seems ample evidence to indicate that the oxygen present in the magma and in the surrounding mineralized zone is not sufficient to insure that all the elements will be in their highest state of oxidation. It is sufficient, however, to insure that much of the iron in igneous rocks may be present as ferric compounds, notably magnetite and hematite. In fact, ferric iron is an important constituent of most igneous rocks, and in the contact deposits and veins formed at high temperatures, ferric iron is abundant in the minerals, magnetite, hematite, garnet (andradite) and other ferric compounds.

In deposits formed at lower temperatures ferric minerals are far less abundant and are often entirely absent, the iron present being in ferrous minerals or in sulphides and allied compounds. Of veins formed at intermediate temperature Lindgren[46] says:

[46] Lindgren, Waldemar, "Mineral Deposits," p. 514, New York, 1913.

Scarcely ever do we find the oxides, such as magnetite, specularite, and ilmenite. The predominating gangue mineral is quartz, but carbonates are also common, such as calcite, dolomite, and ankerite, more rarely siderite; fluorite and barite are occasionally of importance.

In veins that contain abundant sulphate the ferric minerals seem to be at least unusual, though ferrous minerals—siderite or ankerite or manganous minerals—as rhodochrosite or rhodonite may be abundant. Thus in the Cœur d'Alene district, Idaho, Ransome[47] finds that magnetite with garnet is largely confined to the "contact" type of deposits. In most of the veins of the region ferric minerals are absent, though siderite is abundant. Barite is locally abundant.

Spencer[48] recognizes a transition in the so-called "contact" deposits of the Santa Rita district from a zone near the intrusive rock characterized by garnet (andradite) to one characterized by manganiferous siderite and hedenbergite. That is an inner zone where ferric iron predominates and an outer zone where ferrous iron predominates. No sulphates are recognized in these zones. Primary ferrous and manganous minerals in abundance are associated with some of the large ore deposits that are believed to have formed at intermediate temperatures, such as those of Leadville, Gilpin County, Rico, Lake City, and Creede, Colo., Butte and Philipsburg, Mont., and many others. Barite is present in some of the deposits; but it has not been reported from others. It is abundant in some deposits, as those of the Tintic district, Utah,[49] where ferrous and manganous minerals are not abundant, though iron sulphide is plentiful.

The Cactus mine, Utah,[50] appears to offer a good example of the relation of ferric, ferrous and sulphate minerals. In that deposit hematite was abundantly formed. After its deposition

[47] Ransome, F. L., "Geology and Ore Deposits of the Cœur d'Alene District, Idaho," U. S. Geol. Survey Prof. Paper 62, p. 94, 1908.

[48] Spencer, A. C., personal communication.

[49] Lindgren, Waldemar, and Loughlin, G. F., "Geology and Ore Deposits of the Tintic District, Utah," U. S. Geol. Survey Prof. Paper 107, p. 153, 1919.

[50] Butler, B. S., "Geology and Ore Deposits of the San Francisco and Adjacent Districts, Utah," U. S. Geol. Survey Prof. Paper 80, p. 121, 1913.

had ceased siderite, anhydrite, and barite were deposited (see Fig. 40). Pyrite and chalcopyrite were deposited throughout the period.

From a consideration of igneous rocks and different types of ore deposits, it would appear that ferric iron is common and ferric minerals form in nearly all magmas and their emanations at high temperature. Sulphur, on the other hand, does not tend to form combinations that crystallize from magmas. Under some con-

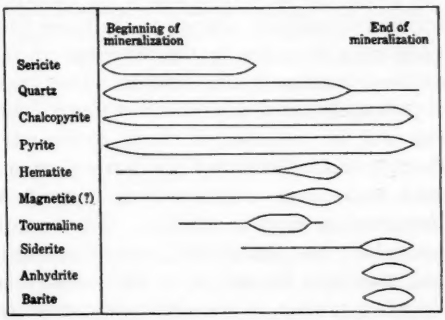

FIG. 40. Diagram showing relative period of formation of the principal ore and gangue minerals of the Cactus ore zone.

ditions sulphur however combines with the metals as sulphides in magmas and may form large deposits or it may be oxidized to sulphate, which may then produce complex silicate-sulphate minerals.

In the contact zone and the deep vein zone the higher oxide of iron continues to be stable and ferric minerals as oxide and silicate are abundantly deposited. Sulphur combines with the metals to form sulphides but they are in large part later than the ferric oxides and silicates, but the sulphate radicle is rarely present and only in silicate minerals. As no insoluble sulphites are formed there is no record as to the presence or absence of the sulphite radicle in the solutions that formed the contact minerals. In veins of moderate and shallow depth ferric minerals are very

scarce or absent, whereas ferrous minerals in some deposits are abundant. Sulphides are abundant and the presence of barite, which is by far the most insoluble of the sulphates, indicates that sulphates probably formed relatively abundantly but for the most part were carried away in solution.

This change from ferric to ferrous minerals, together with the appearance of sulphate minerals associated with the ferrous minerals, may be interpreted as indicating that at the higher temperatures the conditions were favorable to the oxidation of iron and the reduction of sulphur, whereas at the lower temperatures the conditions were favorable to the reduction of ferric compounds and the oxidation of the sulphur. This interpretation agrees with the experimental data so far as the oxidation of sulphur dioxide and the reduction of ferric compounds are concerned. Possibly this reduction of the ferric compounds takes place to some extent even after the ferric minerals have been deposited from the ore-bearing solutions. The hematite in the Cactus mine, which has already been mentioned, is distinctly magnetic and may have become so by the partial reduction of ferric oxide when sulphur or its compounds were oxidized to sulphuric compounds. This record of the ores, then, reveals one possible source of oxygen to form sulphates apart from free oxygen in magmatic emanation. If a large part of the iron in the magma is in ferric and ferrous oxide, the combination of part of the iron with sulphur to form pyrite would greatly reduce the amount of sulphur and at the same time would furnish oxygen to oxidize the excess of sulphur. It has already been pointed out that the iron in the wall rock of many veins as ferrous and ferric oxide has combined, in part at least, with sulphur and thus freed the oxygen to go into some other combination.

The deposits of native copper at Corocoro, Bolivia, are worthy of note in this connection. The deposits are in a series of red sediments. The ore solutions have apparently reduced the ferric iron in the beds containing the ores, and sulphates have been deposited. Miller and Singewald say:[51]

[51] Miller, B. L., and Singewald, J. T., "The Mineral Deposits of South America," p. 92, McGraw-Hill Book Co., Inc., New York, 1919.

The mineral solutions that circulated through the ore beds have bleached them to a white or light green color, but the impervious shales between have not been affected by the solutions. Patches of red sandstone within the ore bodies that have been protected from the bleaching action of the mineralizers are barren of ore. . . . Gypsum and, less abundantly, barite and celestite occur as gangue minerals.

Steinmann, according to Miller and Singewald,[52] believes that:

The mineralizing solutions were analogous to those that formed the other copper deposits of the Andes; that is, characterized by the presence of sulphur and arsenic to the subordination of oxygen. On coming in contact with the ferric oxide of the red beds, they reduced it and bleached those strata, and the sulphur was oxidized to sulphuric acid. On account of the greater affinity of sulphuric acid for lime, magnesium, and iron, the sulphates of those metals were formed and copper was set free.

There is evidence that many of the elements in the magmas besides iron were combined with oxygen and that with decrease in temperature they tended to combine with sulphur. The remarkable deposits at Franklin Furnace, N. J.,[53] are instructive in this connection. There was probably a lack of sulphur in the emanations that formed the deposits, and under those conditions manganic minerals were deposited. Zinc was deposited abundantly as oxide and silicate. In deposits containing sulphides, manganic minerals are certainly rare, though manganous minerals may be abundant and under some conditions manganese sulphide has been deposited. Likewise if sulphur is present in the emanations the zinc oxide and silicate apparently are never deposited, but zinc at the temperature at which it will deposit combines with the sulphur.

It may also be noted that tungsten is most commonly deposited as tungstate but it may be deposited as sulphide. The only known occurrence of the sulphide, that in the Emma mine, Utah,[54] is a

[52] *Op. cit.*, p. 94.

[53] Spencer, A. C., U. S. Geol. Survey Geol. Atlas, Franklin Furnace folio (No. 101), 1908.

[54] Wells, R. C., and Butler, B. S., *Washington Acad. Sci. Jour.*, Vol. 7, pp. 596–599, 1917.

deposit that is believed to have been formed at moderate temperature. Here the sulphide of tungsten was one of the latest minerals to form and apparently in part at least replaced earlier sulphides.

Tin is commonly deposited as the oxide, but in some of the Bolivian deposits which seem to have been formed at only moderate temperatures and in which sulphides are relatively abundant the sulphide of tin was deposited. Some of these deposits contain barite.

Lunge[55] states that "on boiling sulphur with water, hydrogen sulphide is evolved and sulphuric acid is found in the residue." The formation of sulphuric acid by heating sulphur with water has been demonstrated by Allen.[56] Thus hydrogen under certain conditions gives up its oxygen, and the oxygen so released goes to oxidize sulphur. The production of sulphuric acid by the reaction of sulphur dioxide and water at about 150° C. will also take place[57] according to the equation $3SO_2 + 2H_2O = 2H_2SO_4 + S$. The resulting sulphur would of course be available for reaction with water under proper conditions for producing sulphuric acid (H_2SO_4).

If it be granted that sulphates form in the zone of intermediate temperatures without the influence of surface agencies, the question then arises whether a similar origin can be attributed to alunite deposits. There seems to be universal agreement among geologists that alunite deposits have formed near the surface and also that some of them, at least, are formed by acid solutions that result from surface oxidation. It is manifestly difficult to prove the part that surface and deep-seated agencies have played under such conditions, but if barite, anhydrite, and celestite can and do

[55] Lunge, George, *op. cit.*, Vol. 1, pt. 1, p. 17.

[56] Allen, E. T., personal communication.

[57] Lewis, G. N., Randall, M., Bichowsky, R. V., "A Preliminary Study of Reversible Reactions of Sulphur Compounds," *Am. Chem. Soc. Jour.*, Vol. 40, p. 356, 1918.

Randall, M., and Bichowsky, R. V., "Equilibrium in Reaction between Water and Sulphur at High Temperatures; The Dissociation of Hydrogen Sulphide," *Am. Chem. Soc. Jour.*, Vol. 40, p. 368, 1918.

form from deep-seated solutions without surface oxidation, there seems to be no good reason why alunite might not also and why this mode of origin may not be considered if it seems to accord best with the observed facts.

The occurrence of hinsdalite as a primary mineral in deposits that are believed by the geologists who have described them to be of deep-seated (hypogene) origin is of interest. This mineral is chemically closely allied to alunite—in fact is a member of the alunite group of minerals—and if it can form from the same solutions as sulphides, rhodochrosite, and barite, there seems to be no inherent reason why alunite might not also form from ascending solutions under the proper physical conditions.

The geological evidence indicates that alunite can form only at low temperatures, probably considerably below the initial temperature at which sulphuric acid and the sulphates of potassium and aluminum may appear in the solutions.

The mineralogically allied minerals of the jarosite group and other allied basic ferric sulphates are apparently formed only by surface (supergene) solutions, and under near surface conditions favorable for oxidixing iron, where they may form abundantly. It is obvious that they can form only under conditions favorable to the stability of the higher oxides of both iron and sulphur, and it appears that alunite forms under conditions that favor the reduction of the higher oxide of iron to ferrous compounds or sulphide, on the one hand, and that favor the formation of the higher oxide of sulphur, on the other hand.

The fact that ore solutions may change their character during the deposition of the ore has been long recognized. Thus Lindgren[58] in describing the alteration of the rocks adjacent to the veins in the De Lamar mine, Idaho, states:

> This confirms the view set forth that two different processes have been active; first, an ordinary process of sericitization, accompanied by a vein filling of barite and calcite, effected by waters containing alkaline

[58] Lindgren, Waldemar, "The Gold and Silver Veins of Silver City, De Lamar, and Other Mining Districts in Idaho," U. S. Geol. Survey Twentieth Ann. Rept., pt. 3, p. 182, 1900.

carbonates; second, pseudomorphic replacement of the filling by quartz and leaching of Al_2O_3 from the sericitized country rock by siliceous (probably acid) waters.

Lindgren[59] also states that "the loss of so much Al_2O_3 can be explained on the supposition that the waters contained sulphuric acid, as only such thermal waters are known to dissolve alumina in large quantities." In another work he says:[60]

Veins formed near the surface in volcanic regions are sometimes subject to peculiar changes, which are rarely observed in deposits of more deep-seated origin. An earlier gangue mineral, such as calcite or barite, may be wholly wiped out and replaced by a new gangue of quartz and adularia. This alteration has nothing to do with surface waters; it is plainly caused by a change in the composition of ascending currents.

In the San Francisco district, Utah, the writer has described a notable difference in the alteration of the wall rock and in gangue minerals in neighboring deposits in Tertiary lavas which it is believed represent different stages in the process of ore deposition. Thus, regarding the Horn Silver and Beaver Carbonate mines, it is stated[61] that—

Although the principal ore minerals of the two deposits are the same there is a notable difference in the gangue minerals. Carbonates are important in the Beaver Carbonate mine and sulphates in the Horn Silver mine. This difference points to a difference in the character of the solutions that deposited the ores, and a similar difference is indicated in the alteration of the rock adjacent to the deposits. The extensive removal of alumina from the rock of the Horn Silver deposit and the presence of abundant sulphates is contrasted with the failure to remove alumina and the presence of calcite in the Beaver Carbonate deposit.

The presence of sulphuric acid in solution that deposited sulphides is suggested by Spurr.[62] Concerning the alteration of the wall rocks at Tonopah, Nevada, says:

[59] *Idem*, p. 181.

[60] Lindgren, Waldemar, "Mineral Deposits," p. 436, New York, 1913.

[61] Butler, B. S., "Geology and Ore Deposits of the San Francisco and Adjacent Districts, Utah," U. S. Geol. Survey Prof. Paper 80, p. 133, 1913.

[62] Spurr, J. E., "Geology of the Tonopah Mining District, Nev.," U. S. Geol. Survey Prof. Paper 42, p. 234, 1905.

However, they [the mineralizing solutions] attack the rock vigorously by virtue of the carbonic acid, probably also sulphuric acid, and perhaps to a less extent by acids of chlorine and fluorine.

The many known reversible reactions that go on with changing conditions make the problems of changes in ore solutions most complex. These problems really belong in the field of chemistry, but as the reactions that go on in ore solutions as a result of changes in temperature and in concentration may exert a large influence on the deposition of the ores, the geologist may properly point out some of the facts that need explanation and indicate the evidence of the changes that have taken place as they are preserved in the rocks and ores. There are undoubtedly changes of which no record is preserved; indeed, were it not for the presence in ore deposits of a few sulphates that are relatively insoluble, there would be little record of the existence of the sulphate radicle in ore solutions from deep sources. In this paper attention has been directed to some possible relation of sulphur and oxygen to other constituents of ore solutions, but it is obvious that other elements should be considered, of which carbon is an important one.

The possibility of the formation of sulphuric acid and sulphates in magmatic emanations may have a bearing on many problems, but it is not the purpose to pursue their study in this paper. It may, however, be pointed out that close observation of the relations of minerals is essential to a clear understanding. It seems certain that although barite, for instance, does not form at high temperature, it may be associated with minerals formed earlier at high temperature, or even later, as when once formed and perhaps covered with other minerals it might persist, even though the temperature might be raised.

A student of copper deposits, when considering the possibility of a deep-seated source of sulphuric acid, will read with added interest the paper by Zies, Allen, and Merwin[63] on reactions be-

[63] Zies, E. S., Allen, E. T., and Merwin, H. E., "Some Reactions Involved in Secondary Copper Sulphide Enrichment," ECON. GEOL., Vol. 11, pp. 407–503, 1916.

tween copper sulphate and sulphuric acid and various sulphides at moderately high temperature. It seems that there is an almost unlimited field for similar investigation which will contribute directly to the solution of some problems of ore deposition.

SUMMARY.

Sulphates in igneous rocks and in deposits formed at high temperature are confined to a few complex silicate minerals that contain the sulphate radicle. In deposits formed at intermediate temperature barite is common and anhydrite and celestite are not uncommon. Under favorable conditions and probably at comparatively low temperature alunite forms abundantly. In some deposits at least the sulphate radicle of the alunite was probably derived from deep-seated solutions.

A study of volcanic emanations has shown that they exhibit changes in character and that in the later stage of fumarolic activity they may contain sulphurous and sulphuric compounds. Sulphuric acid can readily be formed by the reducing action of sulphur dioxide on ferric solutions. If igneous emanations contain free oxygen and sulphur or sulphur dioxide it would be expected that, as they become cool, sulphur trioxide would be formed, and that at suitable temperature the sulphates would be formed. Sulphur trioxide is unstable at high temperatures and the temperature range in which it forms rapidly and is stable is narrow. If emanations contain no free oxygen that combine with the metals or with hydrogen at high temperatures, they may at lower temperatures combine with sulphur to form the oxides of sulphur and sulphuric compounds.

This interchange of oxygen from certain elements at high temperature to sulphur at lower temperature is believed to be an important factor not only in the formation of sulphates in solutions of deep-seated origin but also in the precipitation of primary (hypogene) ore minerals.

ACKNOWLEDGMENT.

The writer wishes to gratefully acknowledge the criticisms and helpful suggestions of co-workers in the subject of ore deposits, especially those of E. S. Bastin, Adolph Knopf, E. S. Larsen, G. F. Loughlin, Chase Palmer, F. L. Ransome, Max Roesler, A. C. Spencer and R. C. Wells, of the United States Geological Survey; Drs. E. T. Allen, J. B. Ferguson and R. B. Sosman, of the Carnegie Institution of Washington, and Prof. John Johnston, of Yale University, without implying, however, that all these students subscribe to all the ideas put forward.

METHOD FOR PROJECTING STRUCTURE THROUGH AN ANGULAR UNCONFORMITY.

CLIFTON S. CORBETT.

INTRODUCTION.

The discovery of oil in the deeply buried Bend series of north-central Texas and the subsequent development of the newly found productive horizons therein has led to much speculation in regard to the relation of structures in the surface formations to structures in the unconformably underlying Bend formation. The deformation which produced any given local structure in the formations now at the surface affected also the formations lying uncomfortably below and produced a corresponding local structure in them. In an endeavor to determine the nature of underlying structures corresponding to known surface structures the writer developed the method described below for projecting structure through an angular unconformity.

This paper is offered in the hope that the method described will prove of assistance in studying the problems met with in the development of new productive territory in the north-central Texas region and wherever else a similar condition exists. The limitations of the method are great and must not be overlooked. They will be discussed in more or less detail below.

EXPLANATION OF THE METHOD.

In projecting structure through an unconformity three sets of conditions must be known in order to find or work out the fourth or unknown one. These are (1) the general strike and dip of the surface formations, (2) the general strike and dip of the unconformably underlying formations, and (3) the local structure of the surface formations. The unknown condition to be found is the corresponding local structure in the underlying for-

mations. The first and third conditions may be learned by detailed mapping operations carried on in the field (where outcropping beds permit); the second can be learned only from the study of logs of deep borings (in many cases the second condition may be surmised with a fair degree of accuracy from a study of the regional geology).

The method may best be explained by following through with the aid of charts an assumed case. In this assumed case the general strike of the upper series of beds is taken as N. 30° E. and the dip, 50 feet per mile to the northwest; the general strike of the lower series is taken as east-west and the dip, 40 feet per mile to the north. In Chart 1 (Fig. 41) are shown in solid lines

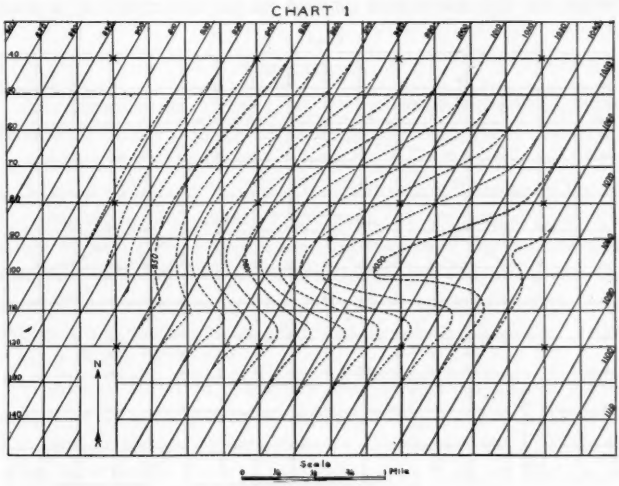

FIG. 41.

the contours for the general strike and dip of each series, an arbitrary elevation being assigned to the respective contour horizons. The contours for the upper series as displaced by an assumed local structure, such as might be mapped in the field, are shown in

dashed lines. For convenience a set of vertical lines is placed on the chart to form a grid system with the east-west contours (horizontal lines) of the lower series. A similar grid system is placed on Chart 2. Also for convenience in referring from one chart to the other corresponding intersections a mile distant from each other are marked by small crosses. At each intersection of the grid system, in the area affected by the local folding, is entered the calculated elevation of the contour horizon of the lower series for that point. Points between intersections may be taken if additional data are needed. With these data the local structure of the lower series is drawn. The elevations of the contour horizon of the lower series are calculated in each case as indicated below for the intersection marked on the two charts by a small

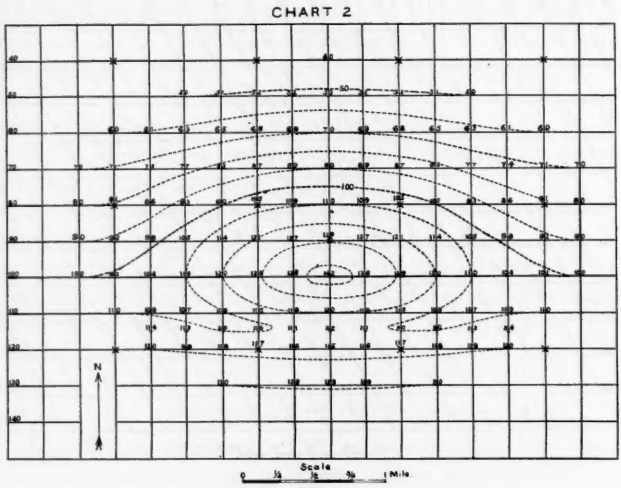

FIG. 42.

circle. At that point the contours on Chart 1 show that the contour horizon of the upper series has been raised from 994 feet to 1,033 feet, that is, a vertical distance of 39 feet. The 90-foot contour of the lower series passed through this point before the

local folding; therefore the present elevation of the same horizon at that point is now 129 feet. The figure 129 is written down at the corresponding intersection of the grid on Chart 2 and the process repeated for every point where an elevation is desired.

Chart 2 shows, by dashed-line contours, the structure in the lower series corresponding to the structure in the upper series as given in Chart 1. The former is the structure which would control any accumulation of oil in the lower series and knowledge of its size and shape is of great importance in directing exploration for oil in the lower series. In the case here assumed it will be seen that the structure in the upper series is a westward plunging nose with a terrace at the top, whereas the structure in the lower series is a well-formed anticline having 30 feet of closure.

LIMITATIONS.

Any combination of the three sets of known conditions may be treated in this manner. There are, however, three important limitations to this method for determining subsurface structure accurately. First there is the uncertainty that the general lay of the underlying beds has been determined accurately from the study of well logs. Well log correlations over any considerable distances are not always satisfactory and in so far as the general lay of the underlying beds as determined differs from the existing condition the projected structure will differ from what it should be.

A second limitation is that the method does not take care of a dying-out or accentuation of folding in depth. For instance, it has been found that where there is a large amount of shale or other incompetent material in the series the folds are likely to be more pronounced in depth. It may be that some of the apparent accentuation of the folds of the Bend formation, mentioned below as probably not to be entirely accounted for by projection of structure through the unconformity, is due to this strengthening of the folds in depth. After a locally productive area has been more or less thoroughly drilled the extent of this accentuation of

structure in depth could be determined by comparing the structure as worked out from well logs for a low horizon of the upper series with the surface structure as mapped. The structure for the lower horizon could then be projected through the unconformity by the method described and the result used for comparison with the structure in the lower series actually worked and from well logs.

The third limitation is that this plan of projecting structure gives a structure for the lower series which represents only the folding that affected the upper beds. In so far as the lower series suffered local folding at a given place before deposition of the upper formations, the structure worked out for the lower beds by the method described will fail to portray the actual conditions at depth. The development of the oil fields of north-central Texas is showing the local folding in the lower series to be more extensive than the corresponding folding of the surface formations and probably more accentuated than would be found by projection of the surface structures to the lower series. The writer's work has not been such as to enable him to collect and thoroughly study sufficient detailed information to compare one or more of the subsurface folds as actually worked out from well records with results obtained by projection of the surface fold to the lower series of beds. It is quite probable that in most localities of structural irregularity in the surface formations there was earlier folding and that the surface structures merely indicate a recurrence of folding along former lines of weakness. Consequently, for this reason as well as that of the probable strengthening of folds in depth referred to above, it is believed that structures projected to the lower series from known surface structures will indicate the minimum size of structure that may be expected at depth.

RESOLVING OF A SUBSURFACE STRUCTURE INTO TWO STRUCTURES ON BASIS OF TIME OF FOLDING.

By a process similar to that employed for projecting structure through an unconformity the amount of structure so projected

may be taken out of the structure actually found from a study of drilling records, and the local structure existing in the lower beds prior to deposition of the upper series may be thereby determined. In this manner a rough measure of the earlier folding may be obtained.

Suppose Chart 3 represents the subsurface structure as actually determined from well logs underlying the surface structure shown in Chart 1. In order to take out of this structure the amount of structure due to the later folding which affected the surface beds, that is, the amount of structure shown on Chart 2, a figure for each intersection of the grid system is obtained as

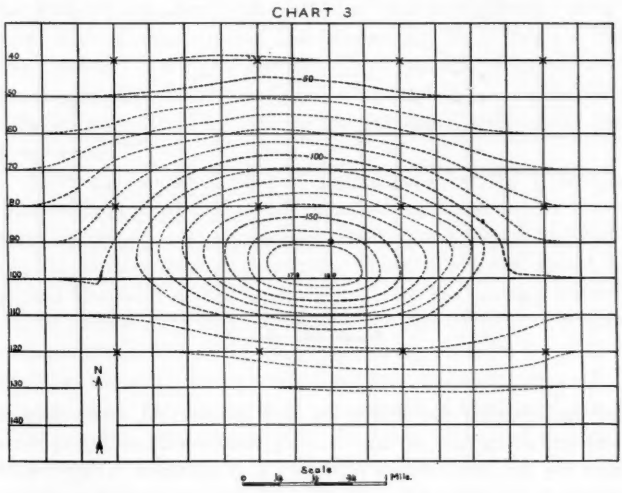

FIG. 43.

follows, using the same intersection as before to illustrate. In Chart 3 the elevation of the contour horizon of the lower series at the intersection marked by the small circle is 167 feet instead of 90 feet as it would have been had there not been any local folding; that is, the contour horizon has been raised 77 feet at this

point. The amount of rise due to the folding which affected the surface beds as determined above was 39 feet. The difference between these two figures, 38 feet, is the amount of rise which took place at this point before deposition of the upper beds. This added to 90 feet gives 128 feet, which figure is entered at the corresponding intersection of the grid on Chart 4. By determin-

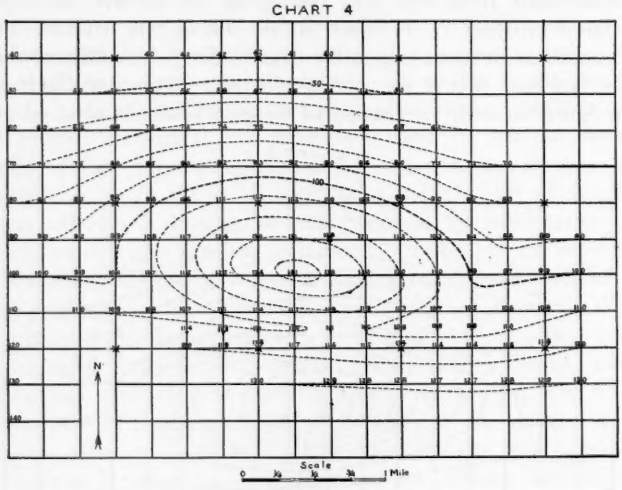

FIG. 44.

ing and entering the figures for each intersection, and points in between where desired, and drawing contours according to these data the structure shown on Chart 4 is obtained, which would represent the local fold before deposition of the upper formations.

The results of thus resolving any given fold into two folds after the area has been more or less thoroughly drilled should be of academic interest in showing the magnitude of the earlier folding. Such an investigation of actual conditions in developed areas may prove of practical value in giving some idea as to what might be expected in other localities of the same region. It is not to be

assumed, however, that the proportions of earlier to later folding would be uniform for the various local folds in any region.

FURTHER APPLICATIONS OF THE METHOD.

Attention is called here to the fact that structure may be projected across more than one angular unconformity just as readily as across one, providing the required sets of conditions are known. The process is merely a transferring of the vertical movement from one series to the other and any intervening series of formations may be disregarded. Thus in those portions of the north-central Texas oil region where Cretaceous rocks cover the Pennsylvanian beds with marked angular unconformity, structures in the Cretaceous may be projected directly through to the Bend series. The more unconformities between the upper and lower series, however, the greater will probably be the difference between the projected structure and the actual structure in the lower series.

Another application of this method of studying structure, which should be of interest to one searching for favorable structures in the field, may be made by reversing the process and finding the kind of surface structures which would correspond to typical favorable structures in the lower series. In this manner can be gained some idea of the type and size of local structures to be sought in field work. In choosing a type case for illustrative purposes the writer took general conditions approximately as they are thought to exist in the north-central part of Eastland County, Texas, and an ideal structure for the lower series and projected it through to the upper series, thereby deriving the assumed structure shown on Chart 1. The resulting westward plunging nose resembles closely the surface structures of some of the productive territory of that area.

CONCLUSION.

It is believed that subsurface structure derived by projection of surface structure will give the nearest approach to actual con-

ditions in a lower unconformable series of beds that can be obtained in advance of drilling. It would follow then that the most favorable locations for first tests in localities where there is some surface structure could be picked from a consideration of the corresponding projected structure in the lower series. In a partially developed region, however, throughout which the general lay of the upper and lower series is uniform, first tests of surface structures might be better located according to some empirical rule derived from results of development of other similar surface structures; this because such a rule may best take care of conditions due to earlier folding which did not affect the upper series. For wild-cat drilling where no empirical rule is to be depended upon, location of tests according to projected structure is recommended.

METALLIC COPPER IN A METEORITE VEIN.

T. T. QUIRKE.

A meteorite which fell June 30, 1918, twenty miles south of Richardton, N. D., affords an interesting occurrence of metallic copper, hitherto unknown in meteorites. The copper is in veins of metallic nickel-iron and iron sulphide. The meteorite is of the veined, gray chondrite type (Cca) of Brezina's classification, composed chiefly of olivine and monoclinic pyroxene, subordinate amounts of glass and troilite, and almost 20 per cent. of an alloy or iron and nickel (Plate XXV *a*).

Minerals.—The minerals of the veins are: (1) An alloy of iron and nickel in the proportion of 10 to 1; (2) troilite, FeS, magnetic iron sulphide, unknown among terrestrial minerals, but very closely related to pyrrhotite, and (3) a few flecks of metallic copper. Iron and nickel constitute about four fifths of the vein filling material, troilite about one fifth, and copper a small fraction of one per cent. Iron and nickel are scattered throughout the stony mass of the meteorite, troilite is scanty outside of the veins, and copper has been found only in the veins. These veins illustrate a type of metallic and sulphide deposits without parallel in ore deposits. They are of interest as illustrative of what has happened under conditions marked by the absence of oxidation agents.

In some veins of the Richardton meteorite, iron and nickel are the dominant vein minerals, containing little blebs and irregular grains of troilite, in other veins troilite is the chief constituent, surrounding globules and irregular pieces of nickel-iron. In two polished sections flecks of metallic copper are included in troilite, which in turn is surrounded by metallic iron (Plate XXV *b*). Three flecks of copper have been discovered on polished surfaces totalling ten square centimeters, the largest piece of copper being about 0.6 by 0.08 millimeters in area.

Mineral Relations.—The relations of the vein minerals to the stony part of the meteorite are not entirely clear. Metallic iron is scattered throughout the meteorite and is concentrated irregularly along the veins. Troilite is irregularly distributed along the veins and is disseminated less abundantly than the metals throughout the groundmass of the meteorite. The outer parts of some of the chondrules are impregnated with very fine grains of troilite, but no iron has been discovered with such relations. Many of the chondrules are partly or completely surrounded by iron and troilite, but none are cracked and penetrated by iron, nor does any surround or include a metallic grain. But since troilite does intrude the chondrules, and since it is syngenetic with the iron, it follows that both metals and sulphide are epigenetic. They have formed in fissures in the stony portion of the meteorite.

Veins.—The veins are only a few millimeters wide, in form resembling fissure veins. In several specimens there are two systems of sub-parallel veins at approximately right angles to one another, similar to common terrestrial fissure systems. In some cases veins are offset slightly by others cutting them, and some split into subsidiary veins, in rare cases reuniting in other places. The veins are clearly planes of weakness, for many small specimens of the meteorite are bounded in part by planes embossed with melted and partly fused blebs and globules of vein material. Merrill[1] notes that many meteorites have veins clearly due to fractures formed previous to their entrance into our atmosphere, and it seems safe to conclude that the veins in the Richardton meteorite follow fracture planes. Other meteorites are known to contain iron and troilite veins, but few show so clearly the syngenetic relation of the metal and troilite.

The manner of the filling of these veins has always been uncertain. Quoting Merrill:[2] "The position occupied by the metallic constituent in a stony meteorite or pallisite is such as to indicate plainly its secondary origin or introduction after the consolidation of all other constituents except the sulphides. While its

[1] Merrill, Geo. P., United States Nat. Mus. Bull. 94, 1916, p. 21.
[2] *Idem*, pp. 20–21.

a

FIG. *a*. Metallic iron and nickel in veins and scattered throughout groundmass of Richardton meteorite.

b

FIG. *b*. Photomicrograph of polished surface of a meteorite vein showing streak of metallic copper imbedded in troilite, itself in contact with metallic nickel-iron.

melting point (about 1500° C. or 2132° F.) is somewhat lower than that of the associated silicates, the manner in which it frequently penetrates the fractures of these constituents (see Admire pallasite) is so strikingly like that of the native copper in the siliceous breccia of the Lake Superior region as to suggest that it results not from a condition of dry fusion, but rather from the reduction of some easily reducible iron-rich compound like lawrencite. Such a reduction, as noted by Nordenskiold[3] and others, must have taken place outside of our atmosphere and in an atmosphere deficient in oxygen."

Referring to the veins in the Farmington meteorite, Farrington[4] writes as follows:

> The following suggestion as to the origin of the veins was made by Preston:
>
> That as the meteor struck our atmosphere the concussion was so great that the mass was fractured in various places, of course extending from the surface inward, and the larger of these fissures or fractures were then filled by the metallic iron which was fused on the exterior surface of the mass due to its velocity through the atmosphere, and was thus forced in a molten state into its present position, thus forming the metallic veins.
>
> This explanation was questioned by Farrington. His conclusion was that the veins were phases of structure of the metallic constituents of the mass, his objections to Preston's view being the following:
>
> (1) The interior of a meteoric mass of any considerable size is so cold that portions of molten metal would be chilled before penetrating to any appreciable distance. (2) The metallic constituents of the Farmington meteorite are its least fusible ones.

It may be added that lawrencite, $FeCl_2$, might be reduced to metallic iron if some means were provided for getting rid of the chlorine. If the stony meteorites contained any stable chloride, that suggestion would be most attractive. However, stable chlorides are unknown in stony meteorites either with or without metal. Furthermore, in the case of Richardton, the suggested introduction of lawrencite does not explain the presence of from 7 to 10 per cent. of nickel, neither does it explain the abundance

[3] Nordenskiold, *Zeits. d. D. geol. Ges.*, 1881, p. 25.

[4] Farrington, O. C., *Nat. Acad. Sci., Mem.*, XIII., p. 187, 1915.

of syngenetic troilite, nor does it touch the matter of segregation of these minerals in veins. In the case of terrestrial deposits we might suggest the introduction of metals and sulphides in aqueous solutions, but meteorites are typically lacking in water. The suggestion that the metals were poured into the crevices while molten during the meteorite's brief passage through our atmosphere is scarcely probable as noted by Merrill and Farrington. However, the Farmington meteorite shows the tops of troilite crystals melted into globules, and little streams of troilite frozen while running in the openings of the meteorite. The troilite in this meteorite might have melted during flight through the air. The Farmington meteorite, however, is unusually porous, and, as it passed through the air, the enormously compressed air in front of it might have penetrated its interior and melted the troilite. According to Ward,[5] a meteorite going 60 miles per second causes the air crowded in front of it to attain a temperature of over 5000° C. by reason of its compression. The Farmington meteorite probably did not fall at such a high velocity, but it probably fell fast enough to compress the air until it reached a temperature considerably above that at which troilite melts. However, such a case could apply only to the most fusible minerals in an unusually pervious and porous meteorite like the Farmington; not to a dense stone like the Richardton, and surely not to metallic iron and nickel, even if it might apply to troilite. Whatever caused the deposition of the iron, deposited also the troilite, for the metal and sulphide are clearly syngenetic. It is clear, also, that the veins were filled previous to the advent of the meteorite into our atmosphere.

The history of the veins seems to be that at some time the meteorite was fractured, later the fractures were filled with iron, nickel, troilite and copper, contemporaneously deposited, and that the veins were filled neither by aqueous solutions nor by fusion of the constituents. First, suppose that the vein material is a concentration of the essential constituents of the meteorite, neither introduced from outside the meteorite nor formed in veins pre-

[5] Quoted by Farrington, *idem*, p. 492.

vious to its separation from some larger body; otherwise the veins, probably, but not necessarily, would be offset or shattered by fractures of a later non-mineralized type. What agencies remain as means of concentration after discarding aqueous solutions and dry fusion? Supposing the concentration of the vein minerals to have taken place while the meteorite was in space, the conditions must have been marked by extreme scarcity of oxygen, water, atmospheric pressure and heat, a coincidence of conditions unknown on our planet. Where so many factors are unknown, hypotheses naturally are advanced with diffidence; however, progress cannot be made except by the examination of alternate working hypotheses.

Eliminating fusion and solution, the only means of movement remaining to the minerals seems to be molecular. Solids have a vapor pressure, which is very small at normal temperatures, and must be much smaller in the extremely cold reaches of space. However, in space the vaporization must be continuous, because a balance can never be attained where the vapors are dispersed as soon as produced. Given time enough, vaporization of solids in space might amount to an appreciable sum. Would the minerals tend more to become inert and stable because of the scarcity of heat than they would tend to become molecularly mobile on account of the reiterated removal of vapor? And if they become more mobile, would the metals and troilite be more mobile than the silicates? If so, would that mobility bring them from the interior of the stone to the exterior and into the fractures? If all that happened, then naturally it follows that the iron, nickel and copper must remain metallic in the absence of oxidizing agents, and whatever sulphur there is would combine with the least easily reduced (and most readily oxidized) metals, forming ferrous sulphide, FeS (troilite), leaving the remainder of the iron, all the copper, and all the nickel in metallic state. The highly speculative nature of these surmises is apparent. A conservative conclusion seems to be that the veins and fractures were formed before the meteorite started on its travels through space, and that no later fractures due to parental disruption happen to traverse

the mineralized veins of the meteorite. According to this hypothesis, the vein filling is a concentration of material scattered throughout the stony mass, which was brought about in the absence of oxidizing conditions by agencies and processes unknown.

The conclusion remains that the Richardton meteorite contains metalliferous veins of iron sulphide, metallic iron, nickel and copper along fractures, which are epigenetic to the stony constituents of the meteorite.

REVIEW OF THE RECENT LITERTURE ON THE TUNGSTEN DEPOSITS OF BURMA.

H. W. Turner.

1. **Bleeck, A. W. G.** On Some Occurrences of Wolframite Lodes and Deposits in the Tavoy District in Lower Burma. *Rec. Geol. Sur. India,* Vol. 43, part 1, pp. 48–74, 2 plates, 1913. Partially reprinted in Min. Res. U. S. for 1912, pp. 998–1000.
2. **Brown, J. Coggin.** Solubility of Tungsten Minerals. *Min. and Sci. Press,* Vol. 115, pp. 302–303, 1917.
3. **Campbell, J. Morrow.** The Ore Minerals of Tavoy. *Min. Mag.,* London, Vol. 20, pp. 76–89, 1919.
4. **Gannett, R. W.** Experiments Relating to the Enrichment of Tungsten Ores. Econ. Geol., Vol. 14, pp. 68–78, 1919. A digest of this paper appears in the *Min. Mag.,* London, Vol. 20, pp. 311–313, 1919.
5. **Griffiths, H. D.** The Wolframite Industry of Lower Burma. *Min. Mag.,* London, Vol. 10, pp. 440–451, 1914.
6. **Griffiths, H. D.** The Wolfram Deposits of Burma. *Min. Mag.,* London, Vol. 17, pp. 60–66, 1917.
7. **Griffiths, H. D.** The Kanbauk Wolfram Mine. *Min. Mag.,* London, Vol. 17, pp. 211–219, 1917.
8. **Jones, W. R.** Mineralization in Malaya. *Min. Mag.,* London, Vol. 13, pp. 195–202 and 322–330, 1915.
9. **Jones, W. R.** Tin and Wolfram Lodes. *Min. Mag.,* London, Vol. 17, p. 230, 1917.
10. **Jones, W. R.** The Origin of Wolfram Deposits. *Min. Mag.,* London, Vol. 18, pp. 319–320, 1918. This is an abstract of a lecture delivered by Dr. Jones at Tavoy.
11. **Jones, W. R.** Tungsten in Manganese Ore. *Eng. and Min. Jour.,* Vol. 106, p. 779, 1918.
12. **Maxwell-Lefroy, E.** Mining in the Tavoy District in Lower Burma. *Min. and Sci. Press,* San Francisco, Vol. 109, p. 448, 1914.
13. **Maxwell-Lefroy, E.** Wolframite Mining in the Tavoy District in Lower Burma. *Trans. Inst. Min. and Met.,* London, Vol. 25, pp. 83–100, 1916.
14. **Means, J. H.** Letter to Hess Describing the Wolfram-tin Deposits of the Mawchi Mines in the Southern Shan States. Min. Res. U. S. for 1912, p. 998.

15. **Rastall, R. H.** The Genesis of Tungsten Ores. *Geol. Mag.*, London, N. S., Decade VI., Vol. 5, 1918.

16. **Scrivenor, J. B.** Tungsten Ores in the Federated Malay States. Abstract in the *Min. Mag.*, London, Vol. 14, pp. 347–348, 1916.

On account of the great demand for metallic tungsten and its products in recent years, descriptions of nearly all districts where tungsten ores occur have been contributed to the geological and mining journals. Of these districts one of the more important is that known as the Tavoy district in Lower Burma, a province of British India. One of the latest articles, by J. M. Campbell, is rather revolutionary in its conclusions as to the origin of these deposits and veins, and hence a general review of the data published may be of interest. Reference to the Mawchi Tin and Wolfram mines of the Southern Shan States is also made as well as those of adjacent districts. Burma, from 1906 to 1917 inclusive, produced about 18,530 metric tons of tungsten concentrates, calculated as of 60 per cent. WO_3 content by Hess and the Mineral Industry. This estimate is for the province of Burma, including the Tavoy and Mergui regions and the Shan States.

Several of the papers noted above describe in detail the methods of mining the ores and their commercial value, but only such data as concern the occurrence and origin of the ores are referred to in this review.

Apparently the most reliable paper on the general geology is that by Bleeck (1). This paper has been abstracted by Rastall (15) and partially reprinted by Hess.[1] In the Tavoy district numerous granite masses are intruded into the quartzites, quartzitic conglomerates and schists of the Mergui series. The biotite granites contain tourmaline and cassiterite as accessories. The wolframite occurs in quartz veins running out from the granite into the sedimentary series; the chief minerals present being quartz and wolframite. The following minerals were observed in all the lodes but in negligible amount: Molybdenite, bismuthinite, pyrite, chalcopyrite, galena, arsenopyrite, columbite in black orthorhombic crystals, and tourmaline in microscopic

[1] "Min. Res. U. S. for 1912."

crystals. Muscovite, a yellow-green lithia-chlorite and green chlorite (penninite) were determined as present. At Kalonta a quartz, muscovite and wolframite occurred close to the quartz-tin and quartz-wolframite veins. In this lode the quartz is of the usual granitic type and the rock may be called a greisen. The micas show a lithia reaction. Wolframite occurs in small crystals scattered through the greisen and tourmaline forms an accessory.

According to their mineral composition, the lodes may be classified into three groups as follows: A, Wolframite-quartz lodes; B, Cassiterite-quartz lodes; C, Wolframite-greisen lodes. Of these the first is by far the most important.

Griffiths (5) in 1914 notes that the Tavoy biotite granite becomes porphyritic near the contact, and that cassiterite as a constituent was found only in the porphyritic facies, or more particularly where this facies merges into a broad band of ferruginous feldspathic rock. The granite-schist contact may be followed from Wagon to Bolin Taung, Kalonta, Chaung, Pa Chaung and Sebalon Chaung. The schist, for a width of twelve miles, measured from the granite contact, contains many mineralized zones of considerable extent, with their main axes parallel with the contact. The schist is much decomposed in the mineralized zones and contains numerous quartz veins which are parallel to the strike of the schists and which form the source of the wolframite. Some veins are also found at right angles to the general strike, close to the granite. Generally these later veins are of greater and more even thickness than those in the schists and where metal-bearing, metallic minerals are more evenly distributed. In all of the mineralized zones, much mica generally occurs on both walls of the quartz veins and in parallel stringers in the schists. The zones vary greatly in thickness as well as in the number and size of the quartz veins that they contain. The proportion of quartz to schist in one zone for a width of 15 feet was 1:4 and in another for a width of 135 feet 1:27. In the case of cross veins, cassiterite has generally been found with wolframite or as an impregnation in the quartzite. No distinction in general can be drawn between the wolframite and the

cassiterite veins as the two minerals are found in the same vein in variable quantities and where cassiterite only is found, it is generally close to the granite or in veins cutting the granite. Evidently the same solutions deposited both cassiterite and wolframite. The former from its greater insolubility was probably deposited first and at greater depth. Unfortunately, the pyritic zone has not been much opened up; in two instances where exposed, the rock became hard and required blasting and the wolframite decreased so as to be unprofitable. The author thinks that the sulphide zone should be exploited as it had not been proven that the wolframite gives out in depth and in any case may be replaced by cassiterite. The wolframite is generally found in sporadic bunches of massive ore; but occasionally more finely divided in small crystals and needles. The muscovite sometimes encloses crytals of wolframite. A little tourmaline is present in the quartz and is more prominent near cassiterite. No fluorspar was observed. Cassiterite is generally found in coarse crystals adhering to one wall only of the vein. When found in conjunction with wolframite each appears to stick to its particular wall. In the upper parts of the veins, geodes are frequently lined with quartz crystals and a little iron oxide, the latter presumed to give evidence of the former existence of wolframite now removed by oxidation.

Griffiths (6) in 1917 speaks of two lodes opened up to the sulphide zone, in both of which the percentage of wolframite was greater in the oxidized upper portion than below. Pyrite increased in depth, and chalcopyrite, bismuthine, cassiterite and molybdenite were noted in small quantities.

Griffiths (7) describes the formation at the Kanbauk mine as consisting of granite, then a belt of decomposed blue rock containing WO_3 from traces up to 1½ per cent., and finally a series of schists dipping toward the granite. The lodes worked appear to be altogether in the sedimentary, in part arenaceous schists, and that contrary to the usual occurrences in Lower Burma, the mineralized zone, carrying the lodes runs at right angles to the strike of the schists. Several minor reverse faults cut the min-

eralized zone which can be traced for a length of about 1,500 feet and a width of 800 feet.

Jones (11) describes alterations of tungsten ores as follows: In most tropical climates, such as Burma, Siam and the Malay States, it is common to find wolframite so weathered that only the hydroxides of manganese and iron, or of tungstic acid remain. In some cases what is left of the weathering of wolframite is almost a pure manganese mineral; in others it is limonite; and in still others no manganese or iron mineral is left, but only the greenish-yellow mineral, tungstite, almost as pure as that obtained in the laboratory.

Whether the wolframite is replaced by manganese minerals, by iron minerals or by tungstite appears to depend upon the following: A, The original composition of the wolframite; B, The composition of the water acting on the wolframite.

A. The wolframite, as found in the countries named, is almost invariably composed of the huebnerite and ferberite molecules in varying proportions.

B. The water generally has an acid reaction due to decaying vegetation and the decomposition of unstable sulphides and arsenides. Occasionally it has an alkaline reaction from the alteration of feldspar. The presence of manganese or iron in solution in the water before it attacks the wolframite appears also to be of importance in determining how the wolframite will weather. The residue most commonly left by the weathering of wolframite in these countries is limonite, but lumps of manganite are fairly common. The tungstite generally occurs as a bloom on the wolframite, and in the cleavage plans and minute fractures.

So unstable is wolframite that at the foot of hills in which there are veins of that mineral which are being worked, it is the exception to find any wolframite in the alluvial deposits, although it is common in detrital deposits, and tin ore, obviously derived from the lodes carrying wolframite and tin, may be present. This is strikingly shown in an alluvial deposit where tin ore is being recovered carrying less than 1 per cent. of wolframite, although occasional rounded pebbles of quartz are found carry-

ing wolframite protected from decomposition by a covering of silica. In conclusion the author gives the following analysis of a manganese deposit in a wolframite lode, occurring in decomposed phyllite. The manganese deposit occurred as a patch in the lode and gave place on both sides to slightly altered wolframite assaying over 70 per cent. WO_3.

ANALYSIS OF MANGANESE ORE BY H. R. PEPPER.

MnO	90.38	Al_2O_3	4.00
WO_3	4.20	SiO_2	1.80

Jones (9) considers that there is conclusive evidence in Malaya and Lower Burma that there were at least two sets of fissures in existence prior to the latest phase of the granite intrusion, which were first filled with the residual acid magma and in this way were formed the numerous pegmatitic and quartz veins of the Tavoy district. He (8) speaks of the abundance of tourmaline and of topaz in the Malayan region and states that so persistent is tourmaline in places that the Chinese call it by a name which means "friend of tin."

Dr. Jones (10) presents evidence of the origin of the tungsten deposits through the action of mineralizers and water originating in the granitic magma; Campbell (3) introduces meteoric waters apparently chiefly because the Tavoy veins are mostly quartz veins of hydrothermal origin as he thinks, and he does not believe a magma can furnish sufficient water to account for their origin. Therefore, Dr. Jones' theory of the origin of tungsten deposits is presented rather fully.

The granitic batholith of this region is probably continuous underneath the surface from the Southern Shan States, through Tavoy, Mergui to the Malay States and through Johore toward Singapore and into the islands of Banca and Billiton. When fissures had formed in the granite due to cooling, shrinkage and to various stresses, the residual more acid magma was intruded into them. Numerous fissures also formed in the adjacent mica-schists, quartz-schists and phyllites. Mineralizers from the magma followed immediately, and often accompanied, the in-

trusion of the very acid residual magma. Upon reaching a temperature zone sufficiently cool, the wolframite, cassiterite, molybdenite, bismuthinite, pyrite, arsenopyrite and a host of other minerals were deposited. The tungsten and tin ores occur where the chilling was greatest, namely chiefly along the walls of the fissures. Also the mineralizers to some extent ascended in the original magma and deposited tungsten and tin ore as original constituents of the first consolidation of the granite.

The mineralizing gases and solutions, acting as powerful fluxes and catalyzer, lowered the temperature of the residual magma. Catalysis can, perhaps, offer an explanation of the influence of such mineralizers as fluorides, chlorides, borates, tungstates, vanadates, etc. These fluxes enabled the magma to be intruded into narrow fissures forming quartz and pegmatite veins, sometimes extending several hundreds yards into the adjacent schists, where the cooling effect must have been great. This bears on the persistence in depth of wolframite. The former existence of mineralizers is shown in Malaya by the abundance of fluorine minerals. But in Tavoy these are not common, and the author thinks that sulphur (why not arsenic?) may have been an important "carrier" of tungsten and tin ores.

Wolframite being regarded as a lower temperature mineral than cassiterite the author still regards the prevalence of tin over tungsten in Malaya as being due to the greater erosion in that region, having eroded the tungsten zone, while in Burma with less erosion, the higher wolfram zone is in greater evidence.

Brown (2) in 1917 presents the same evidence as Jones that in Tavoy with five months of heavy rains yearly, tungsten minerals are rather readily dissolved. They are present in detrital deposits, and absent in water deposits (alluvial), although the lodes contain generally more wolframite than cassiterite. Also, the outcrops give evidence of the former presence of wolframite.

Maxwell-Lefroy (12 and 13) adds little to the geological information. He refers to schist at a distance of over 300 feet from the surface, so decomposed as to be broken with a pick. He also states that cassiterite is *frequently* found enveloped by

wolframite, indicating that the wolframite was deposited *after* the cassiterite. The author states that one vein at the Hpaundaw mine was traced down the hill slope for a horizontal distance of three fourths of a mile and a vertical depth of 1912 feet, showing that persistent veins do occur.

In discussing this paper, W. H. Trewartha-James noted that Dr. Bleeck described a tin lode apparently formed by the reopening of a wolframite lode, showing that the cassiterite was deposited after the wolframite. John J. A. Page, in discussing the same paper, mentions copper minerals, arsenical pyrites and columbite as among the accessories. Page also mentions that there is considerable topaz in some of the veins and that in the area of the upper tributaries of the Khamaunghla, wolframite favored veins in the schists; that cassiterite favored veins in the quartzite; and that veins either of quartz or pegmatite in the granite usually contained both minerals and mentions having traced alluvial cassiterite back to veins which seemed to contain no wolframite and alluvial wolframite back to veins poor in cassiterite.

Means (14) describes briefly the geology of the Mawchi tin-wolframite mines of the Southern Ṣhan States. The tin-tungsten ore occurs in a series of approximately parallel and nearly vertical quartz veins, 3½ to 5 feet wide, which are found both in a boss of granite and adjacent quartzites. Cassiterite and wolframite (or possibly ferberite) are associated with pyrite, a little scheelite, arsenopyrite and some tourmaline in a hard quartz gangue.

Campbell (3) in 1919 appears to have made the most thorough study of the tin-tungsten veins of the Tavoy district yet made. The tin-tungsten ores of Tavoy are found at or near the contact of granite and surrounding sedimentary rocks. The author claims to have identified wolframite, cassiterite and bismuthite (bismuthinite?) as original constituents of the granite magma and also has found appreciable quantities of wolframite and cassiterite in aplite dikes. Greisen occurs on the walls of the veins carrying wolframite or tin and this greisen carries wolframite.

cassiterite and various sulphides. The granite magma is considered the source of all the ores. The veins in Tavoy are mere cracks or fissures in the sedimentary rocks filled with quartz with or without feldspar or mica, through which the valuable minerals are distributed in a more or less erratic manner. The most marked peculiarity of the veins is that they occur in groups parallel and close to one another, often very numerous, very narrow and frequently of limited length. There is often a second series of veins intersecting the first series. Many of the veins diminish in both width and value as they go down. The longest vein yet known extends for several miles from the vicinity of Yewaing, practically parallel to the axis of the granite ridge. It is one of the oldest in the district, has undergone several reopenings and contains tungsten, iron, copper, lead and zinc.

When a number of parallel veins occur close together, wolfram or tin is usually present in greater or less quantity. The granite magma is regarded as a liquid compound largely of silica, with smaller amounts of alumina, alkaline oxides, magnesia, lime, ferrous and manganous oxides; also traces of tungsten, tin, sulphur, carbon, fluorine and boron. After the crystallization of the main components, feldspar, mica and biotite, the left-over mother liquor must have consisted principally of silica and water with some alkalies, lime, alumina, iron and manganese with all the sulphur and ore-metal radicals as well as fluorine and boron, the last two present in very small amount. The author concludes that neither pneumatolysis nor magmatic filling can account for the veins and appeals to surface water, which he thinks reached the magma through fissures at certain points, increasing its fluidity locally and greatly increasing the solvent power of the magma, thereby taking the ore minerals into solution and causing a segregation of them from the magma. The more aqueous portions of the magma would remain liquid after the bulk of it had commenced to solidify at the contact with overlying rocks. Absorption of water continued until the pressure was so high that the overlying strata were burst upward and pressure thus relieved. This would cause the formation of fractures and could take place

only immediately above the liquid aqueous part of the magma, and thus the origin of the numerous parallel veins in circumscribed areas is accounted for. Unless some solvent process was operative just before the solidification of the granite magma and one that brought the ore minerals from below upward, how can we explain the existence near the surface of the granite, of a layer, in some places over 50 feet in thickness, in which cassiterite and wolframite are uniformly distributed throughout the rock. Such occurrences are not uncommon. The granite weathers rapidly and may be worked by ground sluicing. There are considerable areas containing from one to two pounds per cubic yard of such material.

Referring to the pneumatolytic theory, the author states that when chlorine, fluorine and boron compounds are found in veins in adequate quantity, the pneumatolytic theory is credible as an explanation of the origin of the veins, but asks what are we to do with the Tavoy veins that show practically no chlorides, little fluoride and *never* a crystal of tourmaline. There would appear here to be a conflict of testimony for Bleeck and Griffiths found tourmaline in the veins, the former finding it universally present in microscopic crystals and the author himself postulates boron as a constituent of the magma. Moreover, J. Coggin Brown (2) inspector of mines of the region, testifies to the presence of tourmaline in Tavoy, and Means observed tourmaline in the Mawchi deposits in Upper Burma; also Scrivenor (16) and others indicate that it is very abundant in the adjoining Malay States. It may also be noted that topaz, a fluorine silicate, is stated by Page (Discussion of 13) to occur in considerable amounts in some of the Tavoy veins.

The author quotes Lindgren as stating that tin may be deposited at ordinary pressures by thermal waters and refers to Verbach, who describes a hot spring in Malacca which deposits a siliceous sinter containing tin. The author concludes that in Tavoy hot water was the vehicle that transported the tin from the granitic magma. Also that with wolfram the case is even simpler, since

silico-tungstic acid ($SiO_2 \cdot 4H_2O \cdot 12WO_3$) is readily soluble in water.

The veins in the Tavoy district are highly siliceous and may be divided into quartz veins and pegmatite veins. No definite line separates the two. All contain quartz and with few, if any, exceptions, mica, but not of the kind (biotite) found in the granite.

Paragenesis of the Vein Minerals.—Referring to the statement by Dr. Jones (9 and 10) that wolframite is a lower temperature mineral than cassiterite and exhibiting a specimen showing cassiterite deposited on wolframite as an exception, the author states that he has examined the mixed tin-wolfram ores from most of the mines of the district and that in the vast majority of cases there is no doubt that the wolframite was deposited *before* the cassiterite; that he has seen hundreds of examples of cassiterite filling spaces between wolframite crystals, enclosing wolframite and carrying impressions of its striations, several where cassiterite has filled cracks in wolframite and two excellent examples of tin-ore crystals actually formed on surfaces of wolframite, and apparently knows of no instance where the wolframite is the later mineral. Consequently the author warns the mining public that it is hopeless to expect to find a tin-zone below the tungsten zone in the Tavoy veins. Moreover, the author finds that the tin-tungsten content of the veins decreases going down from the granite-schist contact. The succession of the various minerals is as follows; in the order named, the first being the first deposited: Molybdenite, wolframite followed by scheelite in some cases and by cassiterite in others, then bismuth and bismuthinite, chalcopyrite and arsenopyrite, galena and blende. This order is based on examinations of polished sections.

Scheelite is more common than at first supposed. It sometimes develops in veins simultaneously with quartz, the two together filling spaces between crystals of wolframite. Sometimes it develops later, surrounding well-developed crystals of quartz. Secondary scheelite is not at all uncommon, being the result of the action of certain solutions on wolframite. Sometimes it forms pseudomorphs after wolframite from which it was derived.

Molybdenite occurs in non-commercial amounts in many veins. It appears to be characteristic of the zone at or below the bottom of the wolframite zone. Molybdenite is readily oxidized forming molybdite and free sulphur.

Bismuth is known in the native form in only two or three parts of the district. The sulphide, bismuthinite, is somewhat more widely distributed. It occurs in the same veins with wolframite, cassiterite and molybdenite, often in contact with the two former, and also associated with them as a primary mineral in granite. Bismuthinite when exposed to air oxidizes to a pale yellow basic carbonate, bismutite.

The various sulphides, chalcopyrite, arsenopyrite, pyrite, pyrrhotite, galena and blende are not of economic importance in the Tavoy district. Pyrite is ubiquitous. Pyrrhotite alters to pyrite, a somewhat peculiar change. Such pyrite is found only between the bottom of the oxidized zone and the surface of the unoxidized sulphide zone and is always associated with galena and blende. Pyrrhotite has been observed in only a few areas and its porosity renders it susceptible to further oxidation, which sometimes takes place very rapidly and in ordinary dry air. Arsenopyrite is found in small quantity in a few veins, and is usually not intimately associated with wolframite.

Magnetite is found in veins in large quantity in some localities, as well as other iron ores. The author does not indicate that these oxides are associated with the tungsten deposits.

Decomposition of Wolframite.—The rapidity of decomposition of a solid substance depends to a great extent upon the ratio of exposed surface to mass. Wolframite in most of its forms breaks up readily along its cleavage planes, giving easy access to solvent solutions. Wolframite is a ferrous-manganous tungstate, the iron and manganese in it existing in a condition prone to take up more oxygen, thus causing the breaking up of the mineral. Since ferrous and manganese compounds act so similarly, it will save much repetition if we regard wolframite as a ferrous tungstate. We shall therefore take iron throughout this argument to include manganese. There is no mineral containing the

basic radical ferrous oxide in any quantity which can withstand for a prolonged period the action of atmospheric oxygen and water; all sooner or later break up, the iron forming ferric hydrate.

Acid decomposition takes place when certain acids come in contact with wolframite; they break up the union of its radicals, taking away iron and leaving tungstic oxide. The bulk of the ground water in the tropics does not contain free oxygen on account of the large amount of vegetable matter in solution, but rain water contains much free oxygen. Such waters, coming into contact with the pyrite of the veins, converts the sulphur into sulphuric acid, which slowly dissolves one or the other of the wolframite radicals. The acid decomposition of wolframite takes place most readily in cases where wolframite and pyrite are in close association; this is the type of deposit that yields the largest masses of tungstite.

Alkaline decomposition takes place when strong alkalies act on the radicals combining with the tungstic oxide. Ground water always contains alkaline carbonates as well as free carbonic acid, which combine with the tungstic oxide, and is thought to take place in detrital deposits deep below water level. The alkaline carbonates dissolve out the tungstic oxide from the wolfram series.[2] If out of contact with oxygen, the excess of carbonic acid combines with iron, manganese, and in the case of scheelite, with calcium, forming soluble bicarbonates and thus both wolframite radicals go away in solution and the tungsten entirely disappears. These processes of dissolution are extremely slow in nature, but the agents mentioned, although useless for dissolving tungsten in the laboratory, when given the necessary time, do their work just as completely as the most powerful reagents the chemist can apply.

Appended to Mr. Campbell's paper are some remarks by J. Coggin Brown, Chief Inspector of the Mines of Burma. Mr. Brown did not see the necessity of introducing meteoric waters to account for the necessary quantity of water to form mineral solu-

[2] Note that Gannett (4) found that carbonates were not solvents of tungsten.

tions, since it was known that the granitic magmas contain much water. He also thought that pneumatolytic action contributed to the formation of the veins, suggesting that sulphur and arsenic might take the place of boron and fluorine as mineralizers. The pegmatitic origin of some of the veins was indisputable, and as there was field evidence of the pegmatites passing into the ordinary quartz veins, the latter may be considered as a final hydrothermal phase of the pegmatites. Some lodes in Tavoy were regarded as quartz-mica-sulphide-wolframite-cassiterite-pegmatites; some in Mergui and Thaton as quartz-mica-tourmaline-pegmatites; and according to Mr. Heron, his colleague, the Byingi lodes in the Yamethin district are quartz-mica-beryl-pegmatites carrying wolframite. There is thus further evidence in the general district of the presence of mineralizers at the time of the formation of the veins, Mergui, where the lodes contain boron, being in Burma not far south of Tavoy, and Thaton, where there is tourmaline, and Yamethin, with beryllium in the veins, being in the southern part of Upper Burma to the north. While beryllium may not have generally been recognized as a mineralizer its associations are certainly with mineralizers and not with ordinary hydrothermal agents. The universal presence of columbium (in columbite) is further evidence of the same order. On the latter basis, Rastall classes the Burma deposits with those of Etta Knob, South Dakota.

In reference to the article by J. Morrow Campbell, it should be noted that this was presented as a lecture at Tavoy and not written up for publication in a scientific periodical. It is evident that Mr. Campbell has accumulated a lot of data which should serve as a basis of a paper accompanied with the necessary detailed descriptions of thin sections, polished surfaces and ore specimens. It would be of much value as a contribution to our knowledge of this class of ore deposits and it is to be hoped that Mr. Campbell will find time to prepare such a paper in the near future.

Gannett (4) has made some interesting chemical tests on the solubility of tungsten ores, which bear directly on the discussion by Campbell on the same subject. But since that paper appeared

in this journal, it is unnecessary more than to refer to some of the results, in part not confirmatory of those of Campbell and others, and to note his general conclusions:

1. Carbonate solutions had no apparent effect on any of the tungsten minerals.

2. Alkali hydroxide solutions had no effect on scheelite, but dissolved tungsten from wolframite.

4. Sulphuric acid alone, and in combination with sulphates of lime, soda, manganese and ferrous iron, dissolved portions of all the minerals.

5. Hydrochloric acid alone, and in combination with chlorides of lime, soda and manganese, had a solvent effect on the minerals.

11. Humic acids are inactive.

13. Except by sodium hydroxide, scheelite is more readily attacked than ferberite or wolframite.

In regard to the possible secondary enrichment of tungsten deposits, Mr. Gannett concludes that tungsten minerals dissolve rather readily, and form soluble salts or colloidal compounds that may remove the tungsten from the outcrop. The tungsten may be leached from its ore bodies without being deposited below. The facility with which tungsten compounds in solution will hydrolize and form insoluble compounds, tends to prevent downward migration of the tungsten, and there are probably no extensive zones of enriched ores like those of copper and silver. In general, secondary tungsten ores are huebnerite and wolframite, rather than scheelite.

EDITORIAL

WHY ORE IS WHERE IT IS.

The old saying—that gold is where you find it—implied that theory and knowledge were of no value in the search for ore and that its presence could be made known only by actually finding it. The idea is still maintained by many, particularly by the practical mining man. However, it is being continually demonstrated by the economic geologist or mining geologist, that not only is ore where you find it, but in considerable part its discovery depends on where and under what conditions search is made for it. As our previous conception of the percentage of copper or of iron necessary to constitute ores of those metals has changed, due to added knowledge of treatment of ores, so our conception of *why ore is where it is* has changed with increased geologic knowledge supplied by field and laboratory work. The old adage must now be discarded and give rise to intelligently directed search, based on geologic principles, whether for increasing ore reserves in regions already being exploited or for mineral in new regions. The research work of our universities and of the government and endowed laboratories, and the field work of our geological surveys and independent geologists, has produced a host of valuable data which gives greater probability of reward for intelligently directed search for ore or oil based on an understanding of geology. The economic geologist who avails himself of all phases of this knowledge is enabled to decipher more readily why a particular ore is where it is.

Ore is where it is, not purely by chance, but by the result of definite processes which operated under certain conditions within the crust of the earth. The economic geologist is like a detective in that he must search for clues and diagnose these processes which gave rise to a certain deposit. For example: Is

a certain ore deposit located in a particular place because of a pre-existing fissure, or a certain favorable rock formation, or its proximity to an igneous intrusion, or to a combination of all of them? Economic geology is not an exact science like mathematics, yet there are certain fundamental principles which underlie the formation of most ore deposits. No two ore deposits are alike in all respects, but with a knowledge of the principles and processes of ore deposition, one is in a better position to ferret out the problems of the particular ore body.

Such a knowledge of principles and processes is required to answer scientifically the question of *why ore is where it is.*

The answer involves, among other things, a knowledge of the different processes which result originally in the concentration of minerals or mineral products which may be valuable; of the source of the materials and the agents of transportation; of the shapes and distribution of preëxisting cavities and their control over ore bodies; of the shapes and characteristics of ore bodies formed by making their own cavities; the effect of the host rock; the action and results of secondary processes, and the tale that may be unfolded by the minerals that make up the deposit. The final careful answer to the question tells most that need be known of the deposit. The answer, in turn, often enables similar places where similar conditions exist, and where similar processes operated to be determined, and search for more ore to be directed accordingly. For example, should it be found that an ore body originated by solutions given off from a nearby intrusive, that fissures of a certain system acted as channelways for the solutions, and that where the fissures intersected certain beds of limestone, replacement ore bodies resulted, then if the same congenial bed of limestone be formed, and fissures of the same age be recognized and projected to cut the bed, the intersection of the two may be a locus for ore. Exploration may then be directed to that place with the reasonable expectation of the search resulting in the finding of more ore. This is one phase of the work of the trained economic geologist.

While the above example applies to the search for more ore in

districts already partly developed, the answers to *why ore is where it is,* gained from a number of places may also be applied to undeveloped districts. It is a generally accepted fact that most ore deposits susceptible to relatively easy discovery have already been found. Most regions have now been at least superficially prospected. The incentive for prospecting on the part of the old-time prospector is not as great as it used to be. Much credit is due to him for bringing to light a large number of ore deposits, and his passing is much lamented. This, coupled with the fact that more attention is directed to the exploitation of large low-grade deposits, and that in the acquisition of new properties, investing capital now gives more weight than heretofore to the expected possibilities of prospects, requires for the discovery and development of more mineralized regions that there should be enlisted all the knowledge and experience gained by economic geologists. The old prospector was a self trained man and more often not trained at all, but the economic geologist has his own training gained from answers as to why ore is where it is. In addition he has the advantage of the experience of the prospectors, and of other countless trained men who have contributed their knowledge to the science.

With the decreasing chances of discoveries by prospectors, and the consequent waning incentive for them to prospect, has not the economic geologist an opportunity to increase the world's mineral reserves by supplementing, or even supplanting, the work of the old time prospector? His field may be not only to examine and report upon the prospects found by the prospector, but specifically to direct the prospector in his search for new mineral areas, and to guide and advise him about his discoveries.

The old saying "Where ore is, there it is," may then fade into historic interest in the light of the application of the geologist's answers to *why ore is where it is.*

DISCUSSION

This department has been established by the editors in order to afford to those interested in questions relating to economic geology an opportunity for informal discussion. Contributions are cordially invited either in the form of discussion of more formal papers appearing in earlier numbers or bearing upon matters not previously treated. Letters should be directed to the Editor, Sheffield Scientific School of Yale University, New Haven, Conn. The full name of the author should be attached to all communications.

THE GULF COAST SALT DOMES.

Sir: On page 456 of your issue of September, 1918, Mr. G. Sherburne Rogers makes the assertion that I attributed the origin of the coast salt domes of Texas to "pressure of ascending artesian waters" and refers as authority to page 263 of a paper of mine, entitled "The Beaumont Oil Fields," published in the *Journal of the Franklin Institute,* volume 154, 1902, which, I may also add, simultaneously appeared in *Transaction of the American Institute of Mining Engineers.* Knowing, however, that I never intentionally made the assertion alluded to, I have re-read the separate of the paper which I have before me now, with painstaking care and have failed to find therein anything whatsoever which justifies the attribution to me of such a theory.

On the other hand, I find that the one and only conspicuous theory set forth in that paper and one which Mr. Rogers fails to report, pertains not to the structure but to the probable origin of the oil and is to the effect that the salt and associaed minerals were probably secondary deposits derived from ascending hot artesian waters along fissures. This hypothesis is one which I at that time considered original. It was stated as follows:

> The writer has in mind an hypothesis, not hitherto advanced, so far as he is aware, which coördinates Captain Lucas's data and explains that which he omitted—the source and distribution of the oil salt islands, sulphur, sulphuretted hydrogen gas, and dolomite. The hypothesis is

offered with hesitation, not as a final explanation, but in the hope that it may be reached. . . .

The hypothesis is as follows: The oil and salt-pockets of the Texas Coastal Plain are probably not indigenous to the strata in which they are found, but are the resultant products of columns of hot saline waters which have ascended, under hydrostatic pressure, at points along lines of structural weakness, through thousands of feet of shale, sand, and marine littoral sediments of the Coastal Plain Section, through which oil and sand are disseminated in more or less minute quantities. The oil, with sulphur, may have been floated upward on these waters, and the salt and dolomite may have been crystallized from the saturated solution.

The channels of these ascending waters may have been in places of structural weakness, such as fissures, which probably at one time continued to the surface, but may have been sealed by the deposition of the later overlapping strata now capping the oil-pools. Such features, when occurring under gentle anticlines, may explain the collection of oil beneath the surface in pools.

However poor this hypothesis of the origin of the oil may have been at the time of its publication, it was in advance of and entirely different from any previously published, and with the exception of Kennedy's theory that the oil is indigenous to the nearby and associated Frio or Fleming clays, it is still the chief one worthy of consideration. It makes no attempt to explain the doming, however, concerning which there are many theories.

Mr. Rogers also omitted any reference to me as the author of the theory which "postulates the deposition of the salt from artesian waters ascending along lines of weakness" and which "are probable the most widely accepted among geologists today," but, upon page 459 of his article, he attributes it to Prof. Gilbert D. Harris, who adopted it in 1909. At the time of the publication of my paper, 1902, and probably for some time later Harris' writings attributed the origin of these salt bodies to lagoonal deposits in the old Cretaceous seas, and it was not until many years after the publication above cited that he adopted the ascensional theory and amplified it by his concept that the dome structure proper may have originated through salt crystallization.

ROBERT T. HILL.

DALLAS, TEXAS.

REVIEWS.

The Potash Deposits of the Punjab Salt Range and Kohat and Suggestions Regarding the Origin and History of the Rock Salt Deposits of the Punjab and Kohat. By MURRAY STUART, D.Sc. Records Geological survey of India, Vol. L., Part I., pp. 28–29, 1919.

The salt deposits described cover an extensive area in the Province of Punjab, extending eastward from the Waziristan frontier, a distance of some 200 miles. They are much folded and tilted and outcrop in many places. Two separate deposits—one in the Kohat district and one farther east along the Punjab Salt Range—have hitherto been considered to belong to two widely separated geologic periods. The Punjab salt was regarded as pre-Cambrian and the Kohat salt as Tertiary. The Kohat salt is gray and schistose. Foliation is greatest on the western edge and gradually diminishes eastward. The Punjab salt is red and banded. Foliation is much less pronounced than in the Kohat district.

In testing an outcrop or an exposure in a mine, for potash, a sample was collected from every band of salt or at intervals of one foot where the bands were thick. Representative material was obtained by removing the weathered surface and taking the sample from six inches inside perfectly fresh salt. The Nurpur mine was examined more thoroughly by drilling holes every ten feet in the walls of drifts and collecting samples every six inches in the drill holes. The materials thus collected were tested for potash by dissolving a measured quantity of the pulverized sample in a fixed quantity of water and treating the resulting solution with perchloric acid, which produced a white precipitate of potassium perchlorate when potassium was present. By using graduated precipitation tubes and comparing the volume of the precipitate with that produced by known quantities of potassium chloride, approximately quantitative determinations were made.

The results of this examination show that no potassium salts and no magnesium are present in the salt deposits at Bahadur Khel, Karak, Guruza, Malgin, Jatta or in the intervening outcrops in the Kohat district; that small quantities of both potassium and magnesium are present at Nandrakka, which lies in the Kohat district nearest the Punjab salt area; and that the Kalabagh mine, the Nurpur mine, the Warcha mine, and the Mayo mine at Khewra in the Punjab salt area contain irregular

and discontinuous seams, rich in potash and magnesium, many of the tests showing 15 per cent. or more of potash. At the same time most of the samples from the Punjab salt area, including the many samples collected in the Nilawan Ravine, gave negative tests for potash. On the whole, the evidence points to the conclusion that no continuous beds of potash will be found in the Punjab Salt Range or in the Kohat district. It appears probable therefore that potash will not be produced from these deposits except possibly as a byproduct in mining salt.

Study of the deposits shows that the salt in the Kohat district is overlain by gypsum and Tertiary rocks, is schistose, contains iron sulphide widely disseminated through interbedded clay, and is free from potassium and magnesium salts; that the salt in the Punjab salt area usually lies below the Purple Sandstone of Cambrian age, occurs in a red marl which forms a brecciated juncture with the overlying Purple Sandstone, is banded and contains irregular seams rich in potash and magnesium; that the salt in the exposures at Naudrakka is intermediate in type between the Kohat and Punjab salt; and that gypsum is now being formed as a contact mineral. The simplest interpretation of the evidence seems to be that the salt in the two districts belongs to the same formation of pre-Cambrian age; that the sedimentary rocks overlying the salt were brought into place by an overthrust along the plane of which gypsum was formed as a contact mineral; and that the salt was originally deposited from an evaporating saline solution in zones somewhat as the deposits at Stassfurt were laid down. The different types of salt represent portions of different zones, more or less modified. Thus the Kohat salt zone corresponds to the anhydrite zone of Stassfurt, the Kalabagh salt zone to something between the anhydrite and polyhalite zones, the Warcha salt zone to something between the polyhalite and Kieserite zones, and the Khewra salt zone to something between the Kieserite and Camallite zones.

The papers are rather diffusely written and abound in repetitions, but the search for potash appears to have been systematically conducted and the conclusions to be well-founded. The hypothesis for the origin of the deposits appears to offer a satisfactory explanation of relations that have hitherto been perplexing.

W. B. Hicks.

SCIENTIFIC NOTES AND NEWS[1]

W. W. LYTZEN, formerly geologist to the Interstate-Callahan Co., is now manager for the Big Ledge Copper Co., at Juron, Arizona.

FRANK C. LORING, of Toronto, has been in London recently.

R. G. HALL, manager for the Burma Mines, has been in London, and is now returning to Burma.

R. E. HORE has resigned as editor of the *Canadian Mining Journal,* and is succeeded by F. W. Gray.

FRANK C. LORING is at present in London.

CHARLES WILL WRIGHT has gone to Rome, where he will open an office as consulting engineer.

SIDNEY J. JENNINGS has been inspecting the Carson Hill mines in Calaveras County, California.

MORTON WEBBER has been engaged in examination work at Globe, Arizona. He is now at the Empire Copper Mine, at Mackay, Idaho, in his capacity of consulting engineer.

THE NATIONAL GOLD CONFERENCE met in conjunction with the American Mining Congress at St. Louis, November 17–21, to discuss problems confronting the gold industry and to suggest a legislative program.

THE SOUTHERN GEOLOGICAL SOCIETY was organized on November 8 as a regional organization to provide bi-monthly sectional meetings of geologists throughout the Southwest, for the

[1] Geologists, mining engineers and others interested in applied geology are invited to keep the editor informed of new investigations of mining districts or scientific studies undertaken by them, together with such other scientific and personal items as may come to their notice.

promotion of fellowship and coöperation, and the exchange of scientific data and views. Publications will consist only of brief extracts. The membership will be drawn from those engaged in geology in the Southwest. The officers are: President, Myron L. Fuller; Vice-Presidents, Wm. Kennedy and Wallace Pratt; secretary, E. W. Shuler; Treasurer, R. B. Whitehead; Council, Robert T. Hill, H. P. Bybee, J. A. Udden, W. E. Wrather, and Chester A. Hamil. Geologists of the Southwest are invited to send applications for membership to the secretary, Southern Methodist University, Dallas, Texas.

THE NATIONAL ACADEMY OF SCIENCES held their annual meeting at Yale University, New Haven, Conn., November 10–12, at which geological papers were read by Reginald A. Daly and W. A. Davis.

C. K. LEITH, chairman of the Geological Department, University of Wisconsin, has been appointed by the National Chambers of Commerce a member of the Metals Committee to meet and confer with foreign members of the International Trade Conference, at Atlantic City, the latter part of October.

ROBERT H. WOOD AND VIRGIL O. WOOD announce the formation of the firm of Wood & Wood for the practice of general petroleum geology with offices at 516 New Daniels Bldg., Tulsa, Okla.

M. Y. WILLIAMS, of the Geological Survey of Canada, is teaching paleontology at Queens University, Kingston, Ontario, for the first half year.

EDWARD W. BERRY AND JOSEPH T. SINGEWALD, Jr., of the Department of Geology, Johns Hopkins University, have returned from a six months' trip to Peru, Bolivia and Chile. The trip was made through the George Huntington Williams Memorial fund.

ALFRED H. BROOKS AND G. C. MARTIN, of the Alaskan Branch of the U. S. Survey, have returned to Washington.

J. B. TENNEY, for many years geologist for the Phelps Dodge Corporation at Bisbee, Arizona, has opened an office at Bisbee to carry on consulting work in mining geology.

CHARLES H. WHITE is in Arizona, and will not return to San Francisco until December.

OLAF P. JENKINS has resigned from the Arizona Bureau of Mines and is now geologist to the Sinclair Consolidated Oil Corporation.

G. B. LYMAN, of the Copper Queen geological office, has started a class in practical geology, in connection with the educational classes offered by the company to its employees.

D. R. SEMMES has taken charge of the Department of Geology of the University of Alabama, succeeding Dr. William F. Prouty, who recently resigned to enter the Department of Geology at the University of North Carolina. Dr. Semmes' oil work will be continued in conjunction with his associate, Dr. J. S. Grasty, with offices at Fort Worth, Texas.

GEORGE W. LUCAS, of the Engineering Department of the Roxana Petroleum Co., has been transferred from Tulsa to St. Louis.

VICTOR C. HEIKES AND B. S. BUTLER, of the U. S. Geological Survey, were recently at the Tintic Standard mine in East Tintic district, Utah.

H. F. BAIN is in the Malay States, inspecting alluvial tin mines.

EZEQUIEL ORDONEZ has opened an office as consulting mining geologist and engineer at Room 24, Isabel la Catolica 25, Mexico City.

SIDNEY H. BALL has been made a Chevalier of the Belgian Order of the Lion, in recognition of his work in developing the mining industry of the Belgian Congo.

E. W. SHAW has recently returned to the United States and is at present again on the U. S. Geological Survey.

WILLET G. MILLER has returned to Toronto from London.

J. MACKINTOSH BELL has opened a consulting office in Toronto.

W. H. GOODCHILD has gone to South Africa.

MALCOLM MACLAREN has returned to London from Bucharest.

A. MCINTOSH RIED has been appointed Assistant Government Geologist for Tasmania.

THE GEOLOGICAL SOCIETY OF AMERICA will hold its 32d annual meeting in Boston, December 29 to 31, with headquarters at the Copley Square Hotel.

THE WEST VIRGINIA GEOLOGICAL SURVEY has just published: "Detailed Report on Fayette County," by Ray V. Hennen. The volume contains 1,002 pages, 24 plates, 24 figures and topographic and geologic sheets of the area. The New River or Smokeless coals of the area are considered in detail. Price, with maps, $3.25. Extra topographic sheets 75 cents geologic map $1.00. West Virginia Geological Survey, Box 848, Morgantown, W. Va.

LOUIS VALENTINE PIRRSON, professor of physical geology in Yale University, died at his home in New Haven, Conn., on December 8.

ECONOMIC GEOLOGY regrets the necessity of raising its subscription price from $3.50 to $4.00 per year, commencing with No. 1 of Volume XV., January, 1920. This action was deferred as long as possible in the hope that the necessity for it could be avoided, but, as with similar journals, the increasing costs of publication have made it compulsory. New paper and printing contracts have increased that part of the publication by more than 40 per cent. The Journal asks the tolerance of its subscribers in this step and hopes that it may count on them for coöperation by continuing their subscriptions.

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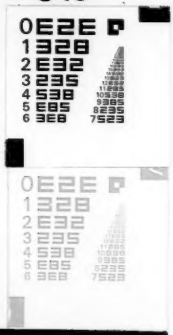
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